



Topic
Science
& Mathematics

Subtopic
Astronomy

My Favorite Universe

Course Guidebook

Professor Neil deGrasse Tyson

Hayden Planetarium
and Princeton University



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and Visiting Research Scientist and Lecturer,
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Professor Neil deGrasse Tyson was born and raised in New York City, where he was educated in the public schools through his graduation from the Bronx High School of Science. Tyson went on to earn his B.A. in Physics from Harvard and his Ph.D. in Astrophysics from Columbia University.

Tyson's professional research interests include star formation, exploding stars, dwarf galaxies, and the structure of our Milky Way. Tyson obtains his data from telescopes in California, New Mexico, Arizona, and the Andes Mountains of Chile.

In addition to dozens of professional publications, Dr. Tyson has written, and continues to write, for the public. Since January 1995, he has written a monthly essay for *Natural History* magazine under the title "Universe." Tyson's recent books include a memoir, *The Sky Is Not the Limit: Adventures of an Urban Astrophysicist*; the companion book to the opening of the new Rose Center for Earth and Space, *One Universe: At Home in the Cosmos* (coauthored with Charles Liu and Robert Irion), which won the AIP science writing prize for 2001; and a playful question-and-answer book on the universe for all ages, titled *Just Visiting This Planet*. Also, premiering in the fall of 2004, will be a four-part PBS-NOVA special on *Cosmic Origins*, hosted and narrated by Tyson.

Tyson's contributions to the public appreciation of the cosmos have recently been recognized by the International Astronomical Union in its official naming of asteroid "13123 Tyson." On the lighter side, Tyson was voted

“Sexiest Astrophysicist Alive” in the November 14, 2000, issue of *People Magazine*, the publication’s annual “Sexiest Man Alive” issue.

Tyson is the first occupant of the Frederick P. Rose Directorship of the Hayden Planetarium, and he is a Visiting Research Scientist in Astrophysics at Princeton University, where he also teaches. Tyson lives in New York City with his wife and two children. ■

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My Favorite Universe

Scope:

This series of lectures discusses 12 topics based on 12 hand-picked essays out of 100 or so written for *Natural History* magazine since 1995. Although they do not follow a particular curriculum, they nonetheless represent the professor's favorite cosmic subjects. And, not surprisingly, they represent topics for which the general public harbors a sustained and insatiable interest.

The dozen lectures are thematically arranged in four groups of three. The first group might be entitled "On Being." Here, Professor Tyson introduces the fundamental properties of matter and energy and the forces that shape the cosmos. Describing these properties and forces as though they are protagonists on a cosmic stage, Tyson shows how the same laws of physics discovered here on Earth reveal themselves elsewhere in the universe, lending extraordinary confidence to the enterprise of science.

The next group of three lectures comes under the heading "Cosmic Catastrophes." Here, Professor Tyson highlights a battery of destructive cosmic phenomena and the role catastrophe has played in the history of life on Earth and in the history of Earth as a planet. The lectures include detailed descriptions of all the things that are bad for you, including black holes, the death of the Sun, and killer asteroids.

The next group of three lectures might be called "The Big Bang." For these lectures, Professor Tyson examines the frontier of our understanding of the universe and asks our most basic questions: How did our universe get here? How has it evolved in the past, and how will it evolve in the future?

Finally, the last group of three lectures addresses the most intriguing quest of them all: "The Search for Life in the Cosmos." Does life exist elsewhere? In what environments would we expect to find life? What would that life be like? Would we recognize alien life if we saw it?

The mission of the dozen lectures in *My Favorite Universe* is to pique your interest in some of the most fascinating and fundamental questions ever asked—questions that have been with us across time and across cultures. In the end, we will know that we have succeeded when “my favorite universe” becomes “your favorite universe.” ■

On Being Round

Lecture 1

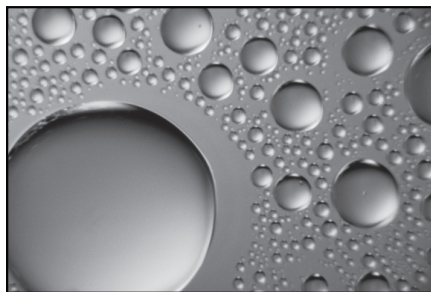
Look around at all the round things in the world. Is there anything nature makes that's not round? Yes, there is. There are a few things. To name a couple, crystals are not round. ... Plus, you have fracture rocks. Those have angles to them. But, by and large, if you look around in the cosmos, there are very few things that make angles.

Let us begin by describing the property of “roundness.” What forces tend to shape objects into roundness, and why is a sphere the most efficient shape that objects can take? From our discussion of spheres in nature on Earth, we move to spheres in the cosmos. Some planets are perfect spheres, but others are not, which in itself tell us something about their environments. As you will see, our description of roundness will take us across the cosmos.

Why are so many things in the universe round? The forces that make things round operate on small and large scales. The term *round* refers to the energy of a body. Energy tends to descend to the lowest energy state it can; for example, think of a house of cards. Some things in the universe, such as crystals, are not round; this fact also tells us something about these objects.

Many natural objects, however, are round, such as soap bubbles, stars, planets, and galaxy halos. Even the observable universe is a perfect sphere, centered on us. This “roundness” is the result of forces that want to shape an

object in such a way that the surface is minimized. Think, again, of soap bubbles. No matter the cavity through which you blow the soapy liquid, what comes out the other side is a sphere. The sphere is the shape that encloses the



Water droplets on glass.

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largest volume with the least surface. If the bubble were any other shape, it would have to stretch itself to cover the surface area. Any other shape would not be as strong as a sphere; it would be thinner in one place than another, and the bubble would pop.

This generalized feature is also revealed in a cube. Some parts of the cube are more distant from the cube's center than others. Every corner is farther from the center than the middle of the cube's sides, which weakens the sides. If the cube were an orb that had gravity—like a planet—the corners would be mountains, and the forces that had enabled gravity to have made the planet in the first place would tend to make those mountains smaller. A rock on the mountain would roll down and fill up the center of the orb. This process would continue until the cube much more closely resembled a sphere.

Other spheres in the universe include raindrops, which are not really tear-shaped but perfect spheres. The force that holds a raindrop together is surface tension—the boundary between a liquid and the air. In forming that boundary, the molecules of the liquid grab onto each other to establish the surface. The act of establishing the surface creates a tension that wraps the liquid. When it falls, the raindrop wraps itself into a perfect sphere, once again, making itself the most efficient shape that it possibly can.

Another perfect sphere is a ball bearing, but how is one made? It can't be produced with a lathe, because it is too small. Ball bearings can be made by dropping liquefied metal down a tube. As the metal travels down the tube, it cools and hardens into a perfect sphere. If you were in a weightless atmosphere, such as the space station, you could squeeze the liquefied metal from an eyedropper, and it would cool and harden and form a perfect sphere right in front of you. In fact, in a weightless atmosphere, you could produce the most perfect ball bearings ever made. Mercury is the only metal that is liquid at room temperature, but its surface tension is so high that it forms a sphere under normal conditions on Earth. Think of the toys that children used to play with in which a mercury bead traveled through a maze. If a sphere maximizes volume and minimizes surface area—in other words, given that a sphere is the most efficient shape—why isn't everything a sphere? Why not packaging in the grocery store, for example? Because spheres roll, that's why. Can you imagine trying to stack round boxes of Cheerios?

As we know, spheres also exist in the solar system. The Sun, which is a star, is a perfect sphere of gas. All the gas in the Sun tends to get as close to the center of gravity as possible to minimize how much total energy is expressed in that field of gravity. Saturn is one-tenth the size of the Sun and is a slightly flattened sphere. The fact that Saturn is not a perfect sphere tells us something about what's going on in Saturn's environment. The Earth, another sphere, is one-tenth the size of Saturn; the Moon is one-fourth the size of Earth. Gravity transforms all these objects of different sizes into spheres.

Does gravity ever fail in its attempt to turn things into spheres? Yes. When an object is small and its field of gravity is weak, it will not become a sphere. Phobos, a moon of Mars that is one-tenth the size of our moon, is not spherical. Phobos does not have enough gravity to have wrapped itself into a sphere. Gaspra, an asteroid that is one-tenth the size of Phobos, is also not a sphere. The chemical bonds of the elements that make up these objects are stronger than the force of gravity, and gravity is helpless in its attempts to turn these objects into spheres. Our own bodies serve as another example.

You might note that some of these objects that we have been referring to as perfect spheres do not seem "perfect" to us. Earth, for example, has craters, cliffs, valleys, and mountains. Keep in mind, however, that the deepest part of Earth's crust, the Marianas trench, is 35,000 feet, or about 6 miles, down. The highest point on Earth's crust, Mount Everest, is about 29,000 feet, or about 5 or 6 miles, up. The total distance, then, between the deepest and the highest points on Earth's surface is 12 miles. This fluctuation is 1/600 of the diameter of the globe. If the Earth were shrunk down to the size of a cue ball, it would be absolutely smooth—a perfect sphere.

Why are some things in the universe not spheres? Tidal forces pull some objects out of a spherical shape. The side of an object that is closer to the force of gravity will feel more gravity than the other side and will be pulled in the direction of the gravity. The Moon exerts tidal forces on Earth. The oceans respond to the fact that one side of the Earth is closer to the Moon than the other. The oceans on the closer side bulge out, resulting in high tide. The oceans on the other side also bulge but to a lesser degree. The oceans on the perpendicular sides experience low tides.

The same tidal forces can be seen in binary stars, where two stars orbit each other. If one of these stars is a black hole and one is a blue or red supergiant, the tidal forces can become so great that some of the material from the giant will be funneled toward the black hole.

As the black hole fills up, the side of the giant closer to the black hole feels an extra tug and its shape becomes distorted. Ultimately, it will resemble a Hershey Kiss.

If the Earth were shrunk down to the size of a cue ball, it would be absolutely smooth—a perfect sphere.

If one object comes too close to another, tidal forces can rip the first object apart.

In the case of Saturn, an asteroid or comet came too close to the planet, and Saturn's gravity ripped it apart and scattered its material into a ring. Eventually, the particles of this asteroid or comet will fall out of orbit, and Saturn will lose its ring.

Rotation also affects the shape of objects. In a rotating object, the movement of rotation will begin to collapse, and the object will be affected by what physicists call the *conservation of angular momentum*. This principle states that if an object is big and rotating slowly, as it gets smaller, it will compensate for getting smaller by speeding up. We see this principle in a skater who is spinning on an ice rink.

We see this same phenomenon in gas clouds. The rotation of the cloud preserves the plane, but the cloud itself collapses from top to bottom. The rotation has the effect of flattening the system. This general flattening is also seen in galaxies. In the Milky Way, for example, some stars reveal the skeleton of the sphere that originally existed, but the galaxy has flattened out. Earth, too, is slightly bigger at the equator than at the poles, because it is rotating at the rate of 25,000 miles around each day.

What happens if an object rotates really fast? If an object rotates too fast, it will fly apart. An object must be dense enough to retain its rotation and not fly apart. Some objects in the universe are so tightly packed that they can sustain a very high rate of rotation. Balls of neutrons, known as *neutron stars* or *pulsars*, are the densest state of matter known. A thimble-full of

the material of a pulsar placed on a scale would balance with a herd of 50 million elephants. These neutron stars have such high gravity that they can spin enormously fast without any danger of flying apart. Nothing has a chance of taking shape in this gravity, making neutron stars the most perfect spheres in the cosmos.

Finally, the observable universe is also a perfect sphere. The universe was born 13 billion years ago. From any direction we look, the farthest we can see is 13 billion light years, because at that point, we see the beginning of the universe. Our “visible edge” is 13 billion light years in every direction, and we are at the center of that horizon. ■

Suggested Reading

Feynman, Richard P. *The Character of Physical Law*. Cambridge: MIT Press, 1973.

Questions to Consider

1. Why is it more useful to ask why something is not round than why something is not flat?
2. In general, which are rounder, high-mass objects or low-mass objects? Why?

On Being Rarefied

Lecture 2

There's an old adage, "Nature abhors a vacuum." Wherever there is a vacuum, nature collapses down on it to get rid of the vacuum. We have this idea that somehow a vacuum is rare, or uncommon, or something that nature does not like. I'm an astrophysicist, and my concept of nature is not just what happens on Earth's surface; it's what happens in the cosmos. In the cosmos, in fact, nature loves a vacuum.

In this lecture, we look at rarefied phenomenon in the cosmos. In astrophysics, we use the term *rarefied* to mean "low density." We sometimes hear that a magician pulled a rabbit out of "thin air," but how thin is air, and are other components of the universe even thinner, or more rarefied, than air? This lecture examines those questions.

We know that air is made of nitrogen and oxygen, but how dense is it? How many molecules of air would fit, for example, in a thimble, or about a cubic centimeter? The answer is about a quintillion—about the same number of molecules of air would fit in a thimble as there are grains of sand on an average beach. Air, then, is not really thin, if we are counting molecules.

This quintillion particles of air in a thimble has a certain weight that we call *sea-level air pressure*. *Pressure* is defined as "the force per unit area." Think of it as a weight. Sea-level air pressure is 15 pounds per square inch. Think of a square inch of space on the ground. From that inch, imagine cutting out a 1-inch square column of air that continues all the way up through Earth's atmosphere. If we put that column of air on a scale, it would weigh 15 pounds. Air pressure is the weight of that column of air.

If we put a suction cup over the square inch of ground, we are removing the air that was inside the pressure column and that was balancing the air all around it. Once we remove the air, the full weight of the 15 pounds per square inch is resting on the suction cup, and we can't pick up the suction cup because the atmosphere is pressing down on it. How much force do we need to lift the cup? The answer depends on the surface area of the suction

cup. If it is 10 square inches, then we need a force of 10×15 pounds per square inch, or 150 pounds of force. When we lift up the suction cup, the air immediately flows back in to fill the vacuum that we originally created.

If we travel to Mauna Kea in Hawaii, we are at 14,000 feet above sea level, and the air pressure is no longer 15 pounds per square inch. Because we're higher up, the column of air above us is shorter, and the pressure is about 10 pounds per square inch. Earth's atmosphere extends for thousands of miles. The boundary of our atmosphere can be defined as the place where the density of air can no longer be distinguished from the density of the space between the planets. Most of the air in our atmosphere, though, is compressed down to the lowest levels. In fact, 99 percent of air molecules in our atmosphere are found below an altitude of 50 miles. The atmosphere has some air molecules above that, but the air there is very low density compared with sea level or even with the density on top of a mountain.

Conditions above an altitude of 50 miles are very different from those on Earth. At altitudes of 50 to 100 miles, molecules collide less frequently, and the whole dynamic of their behavior changes. A constant stream of charged particles, called the *solar wind*, travels through interplanetary space and comes near Earth. Because these particles are charged, they respond to the charges in the magnetic field of Earth. Positive charges go to one pole; negative charges, to the other pole; and they spiral down toward Earth's magnetic pole. As these particles travel, they start to collide into Earth's atmospheric molecules at altitudes of 50 to 100 miles, and they never make it farther down. As low as the density is at those altitudes, it is still high enough for these particles to hit air molecules. When the particles of the solar wind hit air molecules, the molecules become "excited" and release light—photons of energy in the form of blue, yellow, and green light. The result is an *aurora*, a display of light in the sky.

Another material in the cosmos that is thin is the *solar corona*, the crown of the Sun. The solar corona can be seen only during a total solar eclipse. When the Moon moves in front of the Sun, the light of the Sun is removed, and we can see its glowing outer atmosphere, which is not bright enough to reveal itself when the Sun is visible.

What is the solar corona? For a long time, scientists believed that it was made up of glowing gas. When the light from the corona was passed through a prism, however, it was broken up and its component colors and elements could be studied. When the light of the corona was studied in this way, scientists found the signature of an unknown element, which was called *coronium*. Later, scientists learned that under the low-density conditions in the outer atmosphere of the Sun and at very high temperatures, iron emits a signature of light. Highly ionized iron—that is, iron that has lost most of its electrons—has an unmistakable spectral signature, but the conditions that would make iron behave in this fashion had never existed on Earth.

Let's move once again out into the galaxy to the asteroid belt, which many of us think of as a dangerous shooting gallery of asteroids. If we compressed the asteroid belt, however, we would find that its mass is, in reality, only 2 or 3 percent of the mass of the Moon. In addition, 75 percent of that mass is contained in four asteroids, and the rest is scattered for 100 million miles in a 1½-billion-mile orbit around the Sun. The asteroid belt has a much lower density and is much less dangerous than what we might think. In fact, four of our spacecraft, *Pioneer 10* and *11* and *Voyager 1* and *2*, went through the asteroid belt without incident.

Let's move again, farther out, into interplanetary space. The density of matter in interplanetary space is 10 molecules per cubic centimeter. Remember that the density of air on Earth at sea level is a quintillion molecules per cubic centimeter. By comparison, interplanetary space is about as good a vacuum as can be created.

In the vacuum of interplanetary space, we find other objects that are also visible but quite thin, such as comet tails. The tail of Halley's comet, for example, is 100 million miles long, yet it is quite thin. If we collapsed the



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Inner corona of the Sun and the “diamond ring” effect.

whole tail to atmospheric density, it would fill a cube that was about $\frac{1}{2}$ mile per side. What are comet tails made of that makes them so visible despite their thinness? Comet tails reflect some light from the Sun and emit some light of their own for having been excited by the high-energy photons of the Sun. A comet tail is a visible stream that has 1000 times the density of interplanetary space, but that is still low density compared with the atmosphere of Earth. Spectroscopy has revealed that comet tails contain cyanogen (CN), a deadly poison. But the density of cyanogen in a comet tail is so low that Earth can pass through the tail, and the poison has no effect on life.

What is the density of the Sun? The Sun is very dense at its core and less so at the surface. The average density of the Sun is about the density of water and of humans. The density of water is 1 gram per cubic centimeter; the average density of the Sun is 1.4 grams per cubic centimeter. A scoop of the average material of the Sun would sink in the bathtub but not that quickly.

In 5 billion years, the Sun will be about to die. It will have swollen up and become a red giant. The Sun will be 100 times bigger in diameter than it is now, but no mass will have been added to it, so its average density will drop to about $1/10,000,000$ of its current density. The surface of the Sun will be very close to Earth, which means that our atmosphere will evaporate, the oceans will boil and evaporate, and life will be vaporized. As Earth orbits the Sun, as rarefied as the Sun's material is, Earth will plow through some of that material. That material will resist the motion of Earth, and Earth will lose its orbital energy and spiral down into the center of the Sun. As rarefied as the Sun becomes as a red giant, it will still impede the motion of Earth.

Interstellar space, which would take about 25,000 years to reach, is even less dense. The density of interstellar space is about $1/10$ of what it is in interplanetary space—a couple of atoms for every few cubic centimeters.

If gas clouds in interstellar space are near a star, they are rendered visible. The star reflects light off the gas cloud, and the molecules of the cloud become excited and release light. Again, another unknown element with a distinct spectral signature was discovered in these gas clouds. This element, nebulium, turned out to be oxygen in a peculiar state of temperature and very low density.

If interstellar space is empty, intergalactic space is even emptier. Intergalactic space has no dust, no comets, no stars, no moons, and no planets, and its density is about 1 atom per cubic meter.

We know that a pressure exists in the cosmos that will never let the galaxy collapse into itself.

A 200,000-kilometer cube of interstellar space has about the same number of atoms in it that are in the air in your refrigerator. Most of the universe is this kind of vacuum.

We know that the universe is expanding and that there is not enough mass in the universe to exhibit enough gravity to halt

that expansion. How much mass, or density of matter, would it take to balance the expansion of the cosmos? The answer is only about 10 particles per cubic centimeter.

Suppose we could create the perfect vacuum, in which there were no particles. What would we measure? The relatively new field of quantum mechanics describes nature on its smallest scale, at the level of atoms. At this level, quantum mechanics finds new forces of physics and new behaviors of matter.

Quantum mechanics predicts that the perfect vacuum couldn't really be a vacuum. A vacuum is seething with virtual particles. Virtual particles are matter/antimatter pairs that pop into and out of existence in such a short period of time that their existence can't be measured. This theory sounds like science fiction, but few have questioned it because quantum mechanics has been correct in its other predictions. These particles popping into and out of existence in a vacuum create a pressure in the environment. Pressure is the density of energy that has the opposite effect of gravity; instead of bringing things together, it pushes them apart. This pressure is called the vacuum energy. If we try to calculate how much vacuum energy is in the universe, we get a number that doesn't make sense; we know that something is wrong with our calculations. But we do know that a pressure exists in the cosmos that will never let the galaxy collapse into itself.

A few years ago, scientists also discovered that the universe has an anti-gravity pressure operating on it, called dark energy. We don't know what it is made of or where it came from. Vacuum energy, however, could explain the existence of dark energy. This is the very frontier of our understanding. As a final question, we might ask, "Is there a limit to nothingness? Is there a place outside of space with even less in it?" ■

Suggested Reading

Tyson, Neil deGrasse, Charles Liu, and Robert Irion. *One Universe: At Home in the Cosmos*. Washington, DC: Joseph Henry Press, 2000.

Questions to Consider

1. How do our best laboratory vacuums compare with the vacuum of interplanetary space?
2. Why is aurora formed so high up in Earth's atmosphere?

On Being Dense

Lecture 3

There are some mysteries to density. My favorite mystery is that a can of Diet Pepsi floats, and a can of regular Pepsi sinks. We may never understand that one.

As a follow-up to our last discussion, this lecture examines what it means to have density. We will talk about different kinds of density, objects in the universe that are extremely dense, and some mysteries of density. We conclude by noting the usefulness of an understanding of density as a tool for thinking creatively about the world.

Density is a ratio of the mass of an object divided by its volume. The result is a measurement, such as 1 gram per cubic centimeter. We can also talk about different kinds of density, such as population density, which involves area, not volume. In determining population density, we ask, “How many people per square mile live in this area?” The range of mass density in the universe is quite large, going from almost nothing to 40 powers of 10.

Some common forms of matter in the universe have extremely high density. A white dwarf, for example, is the hot, dense core of a star that has been released into space in the dying days of the star. This core was once the center of thermonuclear fusion for the star. Its density would be the equivalent of the density of the Sun if it were compressed into the volume of Earth.

Neutron stars, such as the Crab Nebula, have even higher density than white dwarfs. A neutron star is the remnant of a star that exploded at some time in the universe and spread into the galaxy, enriching the galaxy with heavy elements—the active ingredients of life, planets, comets, asteroids, and so on. In the center of the Crab Nebula is a pair of stars, one of which was the exact center of the explosion. That star is the neutron star. The density of the neutron star would be the equivalent of the density of the Sun if it were compressed into an area about 12 miles across. A thimble-full of the material from a neutron star would balance on a scale with a herd of 50 million elephants.

What happens under conditions of extremely high density? If an object is small and has a lot of mass packed into its area, it has a high surface gravity, which wreaks havoc on its immediate environment. If a gas cloud comes too close to a highly dense object in the universe, the gravity of that object draws the cloud in. The cloud spirals around the central point, inner regions spinning faster than outer regions, creating friction and heat. The result is high temperature and high luminosity. This process is a system by which these small, dense objects consume matter. The object is so small that the matter doesn't fall straight down on it but hits the spiral area, or *accretion disk*, on the side. The disk serves as a way to release energy that then descends into oblivion.

Let's examine the densities of some other materials on Earth. Water has a density of 1 gram per cubic centimeter. We know that frozen water is slightly less dense than liquid water because ice floats. Frozen methane, ammonia, and carbon have about the same density as water. These materials make up comets. When a comet travels too close to the Sun, the heat evaporates these materials and helps make the tail, but the core of the comet is made up of these frozen gases. Rocks range in density from 2 to 5 times that of water, and Earth's crust is mostly rock. Metals, such as iron, are 2 to 3 times the density of rock.

We find, for example, some iron on Earth's surface, but most iron has traveled down to the core of the Earth. In the early stages of Earth, when it was still partially molten, heavier things fell to the center and lighter things stayed on top. We also know that the heavier materials are in the core of Earth from earthquake measurements. When earthquakes send seismic pressure waves through the Earth, measurements can be made of the angles of refraction of these waves to construct a profile of density for the Earth. The density of the crust of Earth is about 3 grams per cubic centimeter; the density of the core, 12 grams per cubic centimeter; and the average density, 5½ grams per cubic centimeter. Other metals, such as platinum, gold, and iridium, are much denser than iron. Osmium is one of the densest metals we know of. A cubic foot weighs about as much as a Buick.

Let's look at some peculiarities of density, in our thinking about it and in reality. We usually say "heavy" when we mean "dense," but in some cases,

that phrasing fails us. In the grocery store, for example, you see skim milk, half ‘n half, and heavy cream, but heavy cream is lighter than skim milk—cream floats on top of milk. The *Queen Elizabeth II* weighs 70,000

tons, but if it were not lighter than water, it would sink. Its total mass divided by its total volume, then, is less than 1. The same is true of battleships and aircraft carriers.

The point of infinite density is in the center of a black hole.

We say on Earth that hot air rises, but that only happens if the environment has gravity. If there were no gravity, hot air would stay in the same place. When air is heated, it becomes less dense, and less dense things rise and more dense things sink. Dead fish are less dense than live fish. If a live fish is neutrally buoyant, it has a density of 1, and a dead fish, which floats, has a density of less than 1. Saturn is the only planet with an average density that is less than water. A scoop of material of Saturn would float in a bathtub.

The point of infinite density is in the center of a black hole. The size of a black hole is described as the size of its *event horizon*, or the boundary from which an object can never return because it would have to exceed the speed of light to do so. Black holes are called “black” because even light can’t get out at the speed of 186,000 miles per second.

If black holes consume material, the event horizon gets bigger. What happens to the material? The material continues to collapse—there is no known force to prevent the continued collapse—until all the matter consumed ends up at a singular point at the center of infinite density. The center of a black hole, then, is called the *singularity*.

All the laws of physics that describe a black hole lose their applicability when we carry the matter down to the center of the black hole because of the density. We need a new theory of physics to explain the singularity. We haven’t yet replaced Einstein’s theory of general relativity, which gave us black holes in the first place.

Let’s conclude with a few more mysteries of density. Imagine for a moment that you have a box of marbles. If you add more marbles to the box, you’ve

increased the volume and the mass of marbles—both terms in the equation for density. If one term increases at the same rate as the other, the density remains the same. A small box of marbles has the same density as a large box. One has more volume and weighs more, but they both have the same density. Is the same principle true with other materials? Imagine a box of down feathers. Calculate the volume and the mass, then add that same amount of feathers to the box. Is the volume twice as much? No, the volume is not doubled, because the feathers at the bottom of the box feel the weight of those on top and are squashed. The act of adding feathers to feathers makes the whole denser. You can double the mass and not double the volume.

Earth's atmosphere has the same characteristic as the box of feathers—it is compressible. The lower atmosphere is under much higher pressure than the upper atmosphere. Half of all the molecules of the atmosphere are below 3 miles. Astronomers try to make measurements on mountaintops or in space in an effort to get above as much air as possible so that nothing interferes with their observations. As mentioned earlier, the Earth's atmosphere extends for thousands of miles, to the point where its density equals that of interplanetary space. The space shuttle flies at 200 to 400 miles above the Earth, but even there, it still plows into atmospheric molecules, which slow down its orbit. The space station must maintain extra supplies of fuel to keep itself boosted so that it doesn't fall out of orbit. If the space station were to fall a little, it would descend into a region of Earth's atmosphere that has a much higher density of particles, which would, in turn, slow its orbit a little more and make it fall faster, and so on. The decay of the orbit is exponential.

In addition, every 11 years, the energy level of the Sun kicks up as it goes through the *solar maxima*. The evidence of this is sunspots, extra solar flares and prominences, and other turbulence on the Sun's surface. This activity warms our atmosphere and makes it swell up, putting satellites at risk for having their orbits decay. When the Russians wanted to get rid of the *Mir* space station, they faced the rockets that were normally used to keep the space station buoyant in the opposite direction. The rockets were then burned to slow down the orbit and drop the ship to a lower altitude, where it was exposed to more air and descended even further. This de-orbit burn was done with such precision that the Russians were able to drop the space station straight into the center of the Pacific Ocean. Creative thinking about

density and how it reveals itself in different materials can be a valuable tool in examining phenomena in the universe. ■

Suggested Reading

Tyson, Neil deGrasse, Charles Liu, and Robert Irion. *One Universe: At Home in the Cosmos*. Washington, DC: Joseph Henry Press, 2000.

Questions to Consider

1. What class of cosmic object makes the most perfect spheres? Why?
2. How do the densities of the Sun, humans, and the Jovian planets compare with each other?

Death by Black Hole

Lecture 4

I don't know if you've ever had one of these homemade spaghetti-making machines. You take the semolina dough; you knead it and ... put it in the machine. You squeeze it and out the other side come these long strands of spaghetti. In fact, this phenomenon is officially known as *spaghettification*; its what happens to matter that's descending into a black hole.

Black holes seem to be one of the most fascinating topics in the universe. In this lecture, we'll learn what they are, how they would kill a human being, and how they wreak havoc in the universe. We'll also touch on recent research suggesting that every galaxy has a black hole at its center and how that fact affects our conception of the universe.

A black hole is a region of space in which the escape velocity exceeds the speed of light. Escape velocity is the speed at which an object must be launched for it to escape its environment forever. For a black hole, the escape velocity is the speed of light, which means that even light cannot escape. Escape velocity is correlated with gravity. Objects that have higher gravity have higher escape velocities. On Earth, the escape velocity is 7 miles per second, or about 25,000 miles per hour. A low-mass object, such as a comet, has an escape velocity of 1 meter per second, or 2 miles per hour.

The Moon has an escape velocity of about 2.5 kilometers per second, or about 1 to 1.5 miles per second. Astronauts had to be launched from the surface of the Moon at that speed; otherwise, they would have fallen back. The Sun has an escape velocity of about 600 kilometers per second, or 400 miles per second.

The mass of the object for which we are trying to determine the escape velocity matters, because objects with high mass have high gravity. Size matters, as well. The more compressed an object is, the closer the surface of that object is to its own center. The force of gravity is related both to mass and distance to the center. A black hole might not even have much mass—

maybe just a few times the mass of the Sun—but because it is small, its surface gravity is high and its escape velocity is high. The point of no return from a black hole is called its *event horizon*.

We discovered black holes through Einstein’s general theory of relativity. This theory describes motion, including gravity and the acceleration of gravity. In this theory, gravity is not just a force of attraction between two objects. Gravity curves space. When objects move, they are moving in response to the curved fabric of the universe. Imagine that we live in a two-dimensional universe that is something like a sheet of rubber. Just as that sheet could be warped, the gravity in our three-dimensional universe can be warped. The warp forms a funnel shape in the fabric, and its center would have very high gravity. Objects in orbit cause even more distortions in gravity. A student of Einstein, John Archibald Wheeler, summed up the general theory of relativity by saying, “Matter tells space how to curve; space tells matter how to move.”

Why would matter collapse to form a black hole in the first place? Usually, matter is supported against collapse from gravity. For example, when an object is heated, its atoms or molecules are in constant motion, creating a pressure that resists gravity and prevents collapse. If the object has a high enough mass, however, its gravity can overcome the sustaining gas pressure. Matter can be squeezed together until it is in a state in which atoms are right next to each other. This is what forms a *white dwarf*. Matter can be squeezed even closer until nuclei are right next to each other, forming a *neutron star*, which is the densest matter we know.

What happens if the force of gravity is so high that even the pressure of neutrons can’t support against it? We know of no force of nature that can support an object against such gravitational forces. Once that object exhausts its supply of nuclear fuel and begins to collapse, nothing is available to support it against collapse. The matter in this object descends through its own event horizon. As far as we know, all the mass collapses down to a single point of infinite density and zero volume. That point is known as the *singularity*. General relativity—the theory of gravity—fails at the singularity.

Let's dive feet first into a black hole. If you're falling through space and you begin to descend toward a black hole, the force of gravity grows exponentially. You would start to fall faster, but if you're in a free fall, you're weightless, which means that you would not even notice the acceleration of your fall.

What kills you in your descent toward the black hole is not gravity, but the difference in gravity felt between your feet, which are closer to the black hole, and your head. On Earth, the force of gravity is also greater at your feet than at your head, but you don't feel this difference, because your size is tiny compared to that of Earth. Black holes, however, are themselves tiny, and this size magnifies the difference between the force of gravity at your feet and at your head.

Some evidence suggests that all galaxies have black holes at their centers, some more massive than others.

As you descend toward the black hole, you would begin to stretch under *tidal forces*. The same force that pulls at the oceans on Earth from the Moon would also stretch you. When the tidal forces exceed the chemical bonds of human tissue, you would be torn in half. Then, those two pieces of your body would be torn in half, and so on. Eventually, you are completely torn into countless pieces of biological matter as you descend.

Further, in your descent, you are occupying a space that is getting narrower and narrower, again, like a funnel. Thus, not only are you stretched head to toe, but you are also squeezed shoulder to shoulder. The result is similar to what happens when you feed dough into a pasta machine. In fact, what happens to matter as it descends into a black hole is called *spaghettification*.

Keep in mind that black holes get bigger in exact proportion to how much mass they consume. They can be any size, which is defined as the size of the event horizon. Only small black holes will kill you before you descend through the event horizon. For large black holes, the tidal forces at the event horizon are relatively low and, therefore, less damaging to human tissue. A low-mass black hole—the smallest—causes the worst damage, because the

rate of change of gravity becomes significant as you near the event horizon. In either case, you'll be torn apart. If you're falling toward a small black hole, it will happen before the event horizon; if you're falling toward a large black hole, it will happen after you reach the event horizon.

How do black holes wreak havoc in the universe? Stars frequently travel in pairs, called *binary stars*. As a star in one of these pairs starts to age, it swells up and becomes a red giant. As it gets bigger, some of its material might get too close to neighboring objects, such as a black hole, which will consume it. In this phenomenon, we usually see a disk of material around the black hole, called the *accretion disk*. This is the collection area of gas from the red giant that is feeding the black hole. We also see jets spewing out above and below the black hole. So much material from the red giant is descending into the black hole that it becomes heated up by friction. The resulting energy must escape in these jets.

At these high temperatures, the disk starts to emit ultraviolet light and x-rays. Some black holes in the centers of galaxies are massive, as much as a billion times the mass of the Sun. Such black holes consume whole star clusters. The accretion disks are huge and emit significant radiation. In fact, such an accretion disk can outshine the entire galaxy in which it is embedded.

Black holes were discovered because of the radiation they emit, along with radio waves, all stemming from one tiny spot. At first, scientists didn't know what black holes were. Because the energy profile of a black hole didn't quite match that of a star, they were called quasi-stellar radio objects—*quasar*. A quasar can be understood as a galaxy with a supermassive black hole. It has such high energy coming from such a small spot that it is visible as a star, but it really exists at the edge of the cosmos.

Can a black hole shut down? The event horizon can stretch out so far that the black hole is no longer able to rip things apart, because the tidal forces become very shallow. If the black hole is that large, it consumes material whole and no radiation is emitted. It is possible for a black hole to get so large that it shuts off its mechanism. A black hole can also shut off if it consumes everything that is near it.

Some evidence suggests that all galaxies have black holes at their centers, some more massive than others. This discovery would mean that all galaxies are the same, but they have different properties, such as different masses of the black holes, different rotation rates, and so on. This conception helps us understand galaxies better, because we are starting from a core of similarities. The Milky Way has an “ordinary” black hole at its center. Our black hole is about a million times the mass of the Sun. It is not big enough to have ever looked like a quasar. ■

Suggested Reading

Shipman, Harry L. *Black Holes, Quasars, and the Universe*. Boston: Houghton Mifflin Co., 1976.

Thorne, Kip. *Black Holes and Time Warps*. New York: W.W. Norton & Co., 1994.

Questions to Consider

1. What special feature of small black holes makes them more dangerous than large ones?
2. When an object collapses and occupies smaller and smaller volumes, what happens to its surface gravity? Does it go up, down, or stay the same? Why?

Ends of the World

Lecture 5

The Sun was born about five billion years ago, giving birth not only to itself, but also to the entire solar system. We date Earth back to about 4.6 billion years. The Sun is going to live another five billion years, so we are exactly mid-way. We are middle aged.

This lecture discusses phenomena that could bring an end to planet Earth. When we contemplate such an occurrence, we usually think of a rampant virus that would decimate our species, or global thermonuclear war, or the destruction of the environment. These tragedies, however, would result only in an end to human beings; Earth itself would still exist. We can point to three scenarios that would result in the destruction of the planet: the death of the Sun, the collision of the Milky Way and the Andromeda galaxies, or the heat death of the cosmos. We won't live long enough to see any of these, but perhaps our species will.

The first scenario we'll examine for the end of the world is the death of the Sun. The Sun was born about 5 billion years ago, giving birth to the solar system. According to predictions of its stellar evolution, the Sun will live for about another 5 billion years. The Sun is mostly made of hydrogen and helium. Its surface is a turbulent plasma that experiences strong magnetic fields. The surface temperature is 6000 degrees Kelvin (K); the core temperature is about 15 million degrees K.

The core, where thermonuclear fusion takes place, is stable and is the source of all energy of the Sun. There, the nuclei of hydrogen atoms are brought together to form helium atoms. This act of *fusion* results in a loss of mass and a release of energy. The Sun would tend to collapse under its own force of gravity, but it can't because this energy is working its way out. The thermal energy released by this thermonuclear fusion and the gravitational pressure trying to collapse the Sun are in balance. Therefore, the Sun keeps its same basic shape and same rate of energy output.

The conversion of hydrogen into helium can continue only as long as hydrogen exists in the core of the Sun at certain temperatures. Extremely high temperatures are needed to bring about the fusion of the two protons in a hydrogen nucleus. Because the protons are both positively charged, they would naturally repel each other. High temperatures increase the speed of the particles to the point where they overcome their repulsion and bind together. At the moment the protons touch, the *strong force of nature* takes over to hold them together. When the Sun runs out of hydrogen, a mass of helium will be left in the core. Helium, however, will not fuse at 15 million degrees; even higher temperatures are required.

The Sun has a mechanism to increase its temperature, called *loss of equilibrium*. When no hydrogen is left to support the Sun, it will begin to collapse under its own weight, but the act of collapsing will heat the core. This process of collapsing and heating continues until the core temperature reaches about 100 million degrees K and the helium ignites.

At this temperature, three helium nuclei will fuse into the nucleus of one carbon atom. This fusion releases much more energy than the fusion of hydrogen to helium, which will force the expansion of the Sun.

As the Sun expands, its surface will cool to about 2000 degrees and it will glow red. It will first grow to fill the orbit of Mercury, then Venus, then Earth. At this point, the Sun will occupy about half the sky. Even though the Sun's surface temperature is dropping, Earth will heat up. Eventually, our temperature will become the same as the Sun's because we will be orbiting on the surface of the Sun. As we said earlier, the oceans will boil and evaporate, the atmosphere will evaporate, and all life will be vaporized. As Earth is engulfed, it will run into the gas that is the material of the Sun, which will slow down its orbit. Earth will spiral down into the Sun and evaporate into a puff of smoke.

We do not believe that stars will hit each other in our collision with Andromeda, but a star may come close enough to Earth to pull our planet into a different orbit.

The red giant phase of the Sun will continue until it runs out of helium and is left with a core of carbon. Even higher temperatures are needed to fuse carbon and, again, the Sun will begin to collapse and its temperature will begin to rise. However, the Sun doesn't have enough mass to raise the core temperature high enough to fuse carbon. It stops, then, with a core of carbon. The Sun's outer layers are now so far away that they are only tenuously connected. Eventually, the Sun will dissipate into space. At this point, the Sun is called a *planetary nebula*; its core of dead nuclear material is a *white dwarf*.

Another way the Earth might be destroyed is in a collision of our galaxy, the Milky Way, with the next closest galaxy, the Andromeda. In the 1920s, Edwin Hubble performed calculations using the Doppler effect to determine the speed and direction of other galaxies moving in the sky. He found that the universe is expanding; nearly every galaxy is moving away from ours. Some galaxies, however, are moving toward ours, including Andromeda. It is now 2.4 million light years away, but we are on a collision path with it at the rate of 100 kilometers per second, or one-quarter of a million miles per hour.

It is possible that the Milky Way has some sideways motion that will throw us into orbit around Andromeda, but thus far, most evidence suggests that we are on a plunge orbit down to the center of that galaxy. Because Andromeda has two or three times the mass of the Milky Way, our structure is likely to come out the loser. One light year is 5.8 trillion miles; therefore, this collision will not take place for 5 to 7 billion years. Computer simulations of such collisions reveal that the galaxies involved become twisted and torn by tidal forces and the force of gravity. Such collisions take several hundred million years and, in fact, we can see pairs of galaxies in every stage of collision to verify the computer models.

We do not believe that stars will hit each other in our collision with Andromeda, but a star may come close enough to Earth to pull our planet into a different orbit. This orbit could be disastrous if we are too close to, or far away from, our new star. Earth might also be flung away from any stars, becoming an *interstellar planet*. Our temperature would drop to the temperature of the universe—3 degrees K. Our oceans would freeze and

our atmosphere would liquefy. Some life might be able to survive using the geothermal energy beneath the frozen surface, deep in the Earth's crust.

Finally, the world could end with the heat death of the universe. We know that since the Big Bang, the universe is expanding and accelerating—against the will of gravity, which would try to have it collapse back on itself. This accelerating force of the universe is known as *dark energy*. As the universe expands, its temperature drops. When the universe was 1/1000 of its current size, its temperature was 3000 degrees, and its temperature now is 3 degrees. When the universe expands to 1000 times its current size, its temperature will be 1/1000 of 3 degrees.

In the distant future, all gas clouds will have made all the stars they can with their supplies. All the stars will burn out. Galaxies will start to turn off or move beyond the visible edge of our horizon. The night sky will grow dark. All processes requiring the movement of energy will cease. There will be no earthquakes, hurricanes, or volcanoes. Any such movement creates heat, which will be radiated into frozen space. When these processes shut down, the universe will end—not with a bang, but with a whimper. ■

Suggested Reading

Adams, Fred, and Greg Laughlin. *Five Ages of the Universe*. New York: Free Press, 1999.

Ward, Peter D., and Donald Brownlee. *Rare Earth*. New York: Springer-Verlag, 2000.

Wheeler, J. Craig. *Cosmic Catastrophes*. New York: Cambridge University Press, 2000.

Questions to Consider

1. What happens to planets when two stars come close to each other?
2. What information allows us to deduce that the entire universe will one day reach nearly absolute zero?

Coming Attractions

Lecture 6

We know Earth has been slammed before by some combination of comets and asteroids, because there's evidence in the fossil record. Paleontologists have known for a long time that there are periods in Earth's history where it was teeming with life, then they hit some boundary in the sedimentary rock, and then most life is gone in the next layers.

Statistically, asteroid impacts represent the biggest threat to human civilization from nature. Most are small and do little damage, but a few are large enough to render the entire species extinct. Evidence in the fossil record tells us that Earth has been hit before by such asteroids. One layer of rock will show the Earth teeming with life, while in the next layer, all life is gone. Such extinction was originally attributed to volcanoes or climate changes, but we now know that about every 100 million years, Earth is hit with a deposit of energy sufficient to cause the loss of 50 to 90 percent of all species. This lecture looks at our risks of getting hit with an asteroid and what we can do to avoid such an occurrence.

You have the same chance of being killed by an asteroid as being killed in a plane crash. How is that statistic true? Calculations tell us that every 100 million years, an asteroid will kill 10 billion people. About 100 people may be killed every year in plane crashes. If you multiply 100 people by 100 million years, you arrive at 10 billion people.

To examine the catastrophe of an asteroid impact, let's look at the early formation of the solar system. The solar system began as a large gas cloud with the right mass and material to make one star in its center—the Sun. Material was left behind after this formation, including heavy elements and leftover hydrogen and helium. This gas began coalescing and forming molecules. In turn, the molecules began to form into dust, and the dust began to form into rocks. The result was rocky and icy debris in the universe. Some pieces of this debris were larger than others and had more gravity. These pieces grew by accretion of more debris, building larger masses out

of scattered smaller objects. When such a mass grew large enough, gravity shaped it into a sphere. Ultimately, these spheres became the planets in our solar system.

Not all material in the universe ended up as part of the planets. The universe still has a good deal of debris, and in fact, for 600 million years after the formation of Earth, our planet was still being hit. This is known as the *period of heavy bombardment*. During this period, the impacts were so numerous that the surface of the Earth didn't have time to cool down in between. The surface temperature was high enough to kill any life that might have developed. Low levels of iron in the Moon throw light on how it was formed at this time. Computer models postulate that a Mars-sized impactor hit Earth and threw large chunks of the crust into space, which coalesced and formed the Moon. Earth had already segregated its materials, with iron toward the center and lighter rocks on the surface; it makes sense, then, that the Moon has low levels of iron.

You usually hear that the span between the formation of Earth and the start of life is 800 million years. The correct figure is 4 billion



NEAR Project, NLR, JHU/APL, Goddard SVS, NASA

Eros, the second-largest near-Earth asteroid.

years, because during the 600 million-year period of heavy bombardment, Earth was sterile and life could not have developed. Many of the ingredients of early life—carbon, nitrogen, oxygen, silicon—were brought to Earth's surface by these impacts. In fact, water was brought to the surface by comets. Earth continues to accrete, but the impact rate has become more manageable. We have had enough time between impacts for species to evolve.

What are the leftovers from formation of the solar system? The universe has tens of thousands of asteroids in an asteroid belt. This is a region of the solar system in orbit around the Sun between Mars and Jupiter. The universe

also has trillions of comets, some near and some far. Comets can be viewed as fossils of the early solar system. Most comets and asteroids don't cross Earth's orbit, but some do. We have avoided a major collision for a while simply by being in the right place at the right time. We have identified some comets and asteroids that would do serious damage if they collided with Earth, such as asteroid Eros. Some of these have come fairly close—between Earth and the orbit of the Moon—and we don't usually see them until it would be too late to take action. We have a good deal of evidence that Earth

Geologist Eugene Shoemaker determined that Meteor Crater in Arizona was formed by a meteor impact.

has been hit by these damaging impacts. For example, geologist Eugene Shoemaker determined that Meteor Crater in Arizona was formed by a meteor impact.

Of course, the most well-known impact is the one that resulted in the extinction of the dinosaurs.

This impact event is called the *Cretaceous-Tertiary (KT) boundary*. The boundary is the layer in rock that tells us what happened before and what happened after the event. After the KT boundary, 70 percent of land species became extinct. The impactor in this event was 10 to 20 miles in diameter and hit the tip of the Yucatan Peninsula 65 million years ago. Modern-day mammals owe their origins to this event. The dinosaurs were wiped out, but small mammals survived and had a fresh ecosystem to populate. Without this planet-wide catastrophe, we would not exist today.

What is the force of these collisions? Asteroids hit the Earth at 45,000 miles an hour. Some asteroids explode in the atmosphere, creating shock waves that would flatten houses. A large asteroid that hits the Earth's crust will make a crater and spew dirt into the upper atmosphere, cloaking Earth with a darkened sky and preventing sunlight from reaching the base of the food chain.

The asteroid that took out the dinosaurs had an energy of 100 million megatons of TNT, the equivalent of 5 billion atom bombs. About every 100 years, we are hit with an asteroid that is about 30 meters in diameter and has an energy of 2 megatons of TNT, or the equivalent of 100 atom bombs.

One such event occurred in Siberia in 1908; 1000 square miles of forest was felled and 100 square miles of vegetation was vaporized, but no crater was found. Computer simulation predicts that this destruction was the result of a stony meteorite, about 60 meters across, that exploded in mid-air. Its shock wave and radiant heat killed the forest. We determine the rate of impact by looking at cratering history on the Moon, which experiences no weather and no erosion and, therefore, preserves all its craters. Other planets are also at risk. For example, Jupiter was slammed in 1994 by a train of about two dozen comets that had originally been one comet. Each one of these impacts had enough energy to have caused the extinction of the dinosaurs on Earth.

What can we do to avoid getting hit by a large asteroid? One approach would be to blow it out of the sky, but a direct hit would be necessary. We might also send up rockets to attach to such an asteroid and nudge it out of the way. If we could predict the collision 200 years in advance, we would need to nudge the asteroid only 1 centimeter a second to avoid impact. We need to catalogue every asteroid that is bigger than about $\frac{1}{2}$ mile across. A collision with something of this size could change Earth's ecosystem. We are the only species in the universe that has the technology and the knowledge to protect ourselves, but if we don't take action, we will go the way of the dinosaurs. ■

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Vershuur, Gerrit L. *Impact: The Threat of Comets and Asteroids*. Oxford: Oxford University Press, 1997.

Questions to Consider

1. How does the probability of being killed by an asteroid compare with the probability of dying in a plane crash?
2. If an asteroid or comet hit Earth, how big would it have to be to wipe out civilization as we know it?

Onward to the Edge

Lecture 7

Earth seen from space enabled you to see clouds, large-scale weather patterns, for the first time. ... At around that time in the 1960s, people viewed us as “Spaceship Earth.” I remember distinctly the introduction of that as a phrase into common parlance, “Spaceship Earth.” Before that image, no one thought of us as that. Here we are together, this fragile little world in orbit around the Sun, like a spaceship.

In this lecture, we take a break from the death and destruction of asteroids and the end of the universe to wonder at the enormity of the cosmos and question our place in it. Since the 1960s, people have been inspired and uplifted by images brought back from space. These same images have deepened our conception of the universe, bringing us to the realization that Earth is just one world among worlds unnumbered. This lecture takes us to the limit of our vision and asks what questions remain once we reach those limits.

Another image that is equally inspiring is called “Earth Rise,” taken by the astronauts of *Apollo 8* in orbit around the Moon. This image increased our awareness of our neighbors in space. We came to realize that the Moon has a sky and a horizon and experiences Earth rise, just as Earth experiences the sunrise. The fact that *Apollo 8* did not land on the Moon enabled the astronauts to take this full-color image of “Earth Rise,” the most recognizable photograph ever taken. This image seems more compelling than the earlier black-and-white photos because it is in color. We can see that the Earth is not featureless; it has water, weather patterns, and so on.

In the early 1980s, spacecraft that had been launched in the 1970s finally reached their destinations and began sending back images. These spacecraft included *Pioneer 10* and *11* and *Voyager 1* and *2*. The images from *Voyager* enabled us to see rich detail on the surface of Jupiter. We learned that Jupiter has extreme weather, including a storm system called the *great red spot* that has been raging for at least 300 years. We also learned that a great deal of terrestrial action takes place on the moons of planets in our solar system.

Jupiter's moon Io, for example, has an extremely active volcano. Another moon of Jupiter, Europa, is covered by a sheet of ice that reveals changing patterns of fractures. There may be liquid oceans beneath this ice and even life. These images changed our view of the planets as abstractions from an astronomy textbook to the concrete reality of an existence similar to Earth's. These planets and moons are worlds in themselves, just as Earth is a world.

Such realizations also changed our outlook on our existence. For example, we note that Venus has a runaway greenhouse effect. Its surface is 900 degrees F, hot enough to bake a 16-inch pizza in 9 seconds. Is Earth heading toward a similar environment?

To me, the most profound and thought-provoking image is one brought back from the Hubble space telescope in the 1990s. The Hubble is the first orbiting observatory specializing in visible light. It was launched by the space shuttle and can be repaired in space from the shuttle.

The fact that the Hubble is in orbit above Earth enables us to see the universe without the turbulent effects of the atmosphere. As light comes from the depths of space, it travels in a perfectly straight path, but when it hits the atmosphere, variations in temperature and density cause that light path to be refracted and dispersed. The result is photos that are blurry and unable to reveal fine detail. In contrast, the Hubble is able to send back very high-resolution photos.

Astrophysicists must apply for observing time on the Hubble, and as you might expect, many more applications are submitted than are accepted. As part of the director's discretionary time, a period of 10 consecutive days of exposures was allocated to document the phenomena in a random and unremarkable portion of the sky. The result



"Earth Rise," taken by the astronauts of Apollo 8.

© Apollo 8 Crew, NASA.

of that documentation is the image known as “Deep Field.” The portion of the sky that was selected for this experiment was away from the plane of the Milky Way and in a direction where Earth would not block its view. It was also selected to avoid known clusters of galaxies and contain no stars. The patch of sky selected and photographed by the Hubble telescope is near the Big Dipper, but it is extremely small—1/100 of the area filled by the full Moon in the night sky. You might think of this area as equivalent to the

**We learned that
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storm system called
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for at least 300 years.**

size of Lincoln’s eye on a penny held at arm’s length. A total of 342 photos were taken of this identical portion of sky, then added together to make one high-quality image. Amazingly, this one tiny patch of sky reveals thousands of galaxies. Practically every spot of light in the photo is an entire galaxy much like the Milky Way, containing hundreds of billions of stars each.

Given the precision of the Hubble’s imagery, we can get close to the picture and actually look into the galaxies. We see the structures of galaxies, some with spiral arms, regions of extra star formation, and different colors caused by different colors in the stars. In similar photos taken by ground-based telescopes, these galaxies are just smudges.

The farthest known galaxy in all the catalogues is seen in this image as a red dot. Why is it red? The wavelength of light is stretched as it travels in an expanding universe. If light is stretched, it becomes lower in energy, and red light has less energy than blue light. We see this distant galaxy not as it is now, but as it was 13 billion years ago. It is one of the earliest galaxies known and serves as a signpost for what the universe was like in the distant past.

Can we extrapolate from the Hubble “Deep Field” image? If every patch of sky is similar, how many galaxies are in existence? The answer is 50 billion. And each one of those galaxies contains 100 billion stars. The sheer magnitude and diversity of the cosmos give us pause. Just as pictures of

the planets changed our abstract conceptions of Earth and the solar system, the Hubble “Deep Field” transformed our vision of galaxies. Researchers now train other kinds of telescopes on that field to add information to the picture. For example, the Chandra x-ray telescope reveals the presence of supermassive black holes in the centers of these galaxies.

We have also looked in the exact opposite direction of the Hubble Deep Field to ensure that the original spot is representative. The resulting images of the Hubble Deep Field South reveal a statistical similarity. This new portion of the sky doesn’t look exactly the same as the original, but it has the same number of galaxies, the same distribution of colors, and the same array of shapes and sizes.

Our new understanding of the cosmos poses deeper questions. Are the laws of physics the same everywhere and through all time? Are there as-yet undiscovered laws that will grant us greater insight into our world and the unnumbered worlds in the universe? Do the planets among the stars in those billions of galaxies have life? Do they have intelligent life? Is that life looking at us in the same way that we are looking at it, or are most other life forms engaged in the quest for food, shelter, and sex, as we are on Earth most of the time?

The image of the Hubble Deep Field represents an intellectual journey. As we look at this photo, we have gone beyond stargazing to galaxy gazing—through time and to the edge of the cosmos. ■

Suggested Reading

Voit, Mark. *Hubble Space Telescope: New Views of the Universe*. New York: Harry N. Abrams, 2000.

<http://heritage.stsci.edu>. The Hubble Space Telescope on-line archives.

Questions to Consider

1. What is the primary reason why the Hubble Space Telescope is so valuable to our understanding of the universe?
2. Observing the universe is sometimes said to be like observing through a time machine. What property of the universe makes this so?

Image Credit

The Hubble Deep Field video, produced by Kenneth M. Lanzetta. Raw images courtesy of NASA and the Space Telescope Science Institute. Partially funded by the National Science Foundation.

In Defense of the Big Bang

Lecture 8

What happened in the 20th century was that we came to learn that whatever it is we determine to be true about the universe might only be a subset of a larger truth. We learned that with Newton's laws of gravity.

This lecture is presented in defense of the Big Bang theory, which is often misunderstood and, sometimes, even discounted. Throughout time, people have asked questions about the origins of the universe and, for most of time, the answers to those questions were provided by mythology. The 20th century was the first period in history in which we were able to use the methods and tools of science to answer our questions. We now know without doubt how the universe began, how it evolved, and how it will end.

Why do we believe in the Big Bang theory? Why do we believe that 13 billion years ago, all energy, matter, space, and time in the universe were packed into a primeval fireball, smaller than an infinitesimal fraction of the size of the point of a pin? Regardless of what you may have read or heard, the Big Bang is supported by an overwhelming body of evidence.

In the 1700s and 1800s, theories were put forth in the world of physics that were tested and ultimately came to be called *laws*. Examples include Newton's laws of gravity, motion, and optics. In contrast, the early 20th century saw Einstein's theory of relativity, quantum theory, and the theory of quantum chromodynamics. The terminology has changed from *law* to *theory*.

Modern theories are just as thoroughly tested and just as successful as the ideas that were previously known as laws. In the 20th century, however, we learned that the truths we determine about the universe may be only a subset of a larger truth. For example, Newton's laws of gravity and motion described the everyday environment at everyday speeds. In the 20th century, physicists began to work with the concept of the speed of light, and new theories were needed to account for phenomena that occurred in this new

domain. Einstein's relativity describes high-speed motion. The theory of general relativity didn't force us to discard Newton, but it encloses the phenomena of the universe that Newton described and encompasses other phenomena. Hence, the Big Bang is termed a theory in deference to the idea that it may someday be enclosed in a larger picture.

We must also note that up until the 20th century, we examined phenomena in terms of whether they were consistent with what we would expect given the application of our five senses. For example, if we see something vibrate, we know that it will make a sound. Physics in the 20th century started using new technology, such as particle accelerators and huge telescopes, to explore domains of matter that our senses had never encountered. When we start learning how the cosmos behaves at the tiny level of the particle or the vast level of the universe, our new knowledge falls outside our senses. We can no longer use the criteria of our senses to judge the implications and meanings of phenomena. Theories in these realms must make mathematical sense, however, if not intuitive sense. The mathematics of a theory serves as a logical image of the idea.

A number of experimental pillars support the truth of the Big Bang theory. The Big Bang makes three assumptions, out of which all its predictions follow. These assumptions are:

- The universe is expanding.
- The universe is cooling.
- The universe had a beginning.

Edwin Hubble observed the truth of the first assumption in 1929 when he noticed that almost all the other galaxies in the universe were moving away from the Milky Way at high speeds. Hubble also noted that galaxies that are twice as far away from us are receding twice as fast. That behavior is a signature of an explosion.

Earlier, in the theory of general relativity, Einstein noted that space can be thought of as a fabric that distorts in the presence of matter. The distortion

is what we call gravity. Under general relativity, the expansion of the universe is not galaxies moving through a preexisting space. Instead, the galaxies are embedded in space, and what is expanding is the fabric of space, something like a three-dimensional sheet of rubber. Just a few years after it was proposed, the theory of general relativity was tested by Sir Arthur Eddington, a well-known British astrophysicist. Eddington went on an eclipse expedition, during which he measured the exact positions of stars near the edge of the Sun. On a similar expedition six months later, he took the same measurements and found that the stars were in different locations. During the eclipse, light came past the limb of the Sun, and its trajectory was altered because of the curved fabric of space and time, just as relativity had predicted. The results of this experiment were consistent with the theory of relativity. Individual objects curve space-time. The sum of all the objects in the cosmos curves the cosmos. Space, then, has a structure that can expand or warp.

How do we know that distant galaxies are receding at high velocities? The speed of galaxies can be measured using the Doppler effect as it relates to light. Receding objects shift to the red part of the spectrum. The farther away an object is, the greater its shift to red. General relativity predicts a phenomenon called *time dilation* for events that take place at great distances. If I'm moving away from you and counting off seconds, the farther away I move, the longer it will take my count to reach you. From your capacity to measure, the duration of a second has increased.

Time dilation can be measured in the universe using supernovae, which are high-mass stars experiencing explosive deaths. We know how long a supernova takes to reach the height of its luminosity and how long it takes to recede, a period known as its *light curve*. The light curve seems to be longer for supernovae in distant galaxies, but if we calculate how much longer it is, we find that the result matches exactly with how much time dilation general relativity predicts for that distance.

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In the 1930s, George Lemaître, a Jesuit priest and cosmologist, was the first to connect the discoveries of Hubble and the theory of relativity. He proposed that if the universe is now expanding, in the past, it must have been smaller, and if the universe was once smaller, perhaps it had a beginning. Lemaître also proposed that when the universe was more compressed, it was hotter. At one point, the universe was 3000 degrees K. At that temperature, atoms are ionized, which means that electrons are detached from their host nuclei. If light tries to move through this medium, it is batted around. Light does not travel in straight lines at this temperature; it exists in a kind of fog. As the universe cools, electrons combine back to the atoms, and light freely flows through. The universe is 1000 times bigger now than it once was and is 1/1000 the temperature now than it was, which equates to 3 degrees K.

George Gamow predicted the current temperature of the universe in 1948, a time when we had learned enough about particle physics to know how particles behave under certain conditions. At this temperature, objects emit primarily microwaves, not visible light. Gamow said that the signature of the Big Bang would be found in the microwave part of the spectrum. In 1967, two physicists at Bell Labs, Penzias and Wilson, tried to measure existing signals of microwaves that might interfere with the ability to use microwaves for communication. They found a microwave background signal, the *cosmic microwave background*, that existed everywhere and couldn't be blocked. Other physicists saw this signal as the visible remnant of the Big Bang, now red-shifted to microwaves. How do we know that the microwaves come from the edge of the universe? The energy of microwave light is bumped up as it moves through high-temperature gas clouds in clusters of galaxies. If the cosmic microwave background is truly a background from the edge of the universe, it should have a warmer signature in these clusters, and it does. This finding proves that the microwave background comes from beyond the matter that we can see.

We can also look at cyanogen molecules (CN) to confirm the temperature of distant galaxies, which are also distant in time. CN becomes excited in a bath of microwaves; the higher the temperature of the microwaves, the higher the excitation level of CN. This excitation level in distant galaxies correlates exactly with the predicted (higher) temperature of the universe at the time of the distant galaxy.

One final piece of evidence is found in the levels of certain elements in the universe. We know, for example, that the universe was born with 10 percent helium. Therefore, every part of the universe should contain no less than 10 percent helium, and every part does have at least that amount. In the same way, lithium and beryllium were present in trace amounts at the beginning of the universe. No part of the universe should have any more of these elements than those trace amounts, and no part does.

Astrophysics and particle physics have joined to give us the truth of the Big Bang theory. The theory still has a few problems. For example, 90 percent of gravity comes from an unknown substance called *dark matter*. Similarly, the future expansion of the cosmos is driven by an unexplained phenomenon known as *dark energy*. We can't yet explain these factors in the structure of the universe. These mysteries, however, do not cause us to discard the Big Bang theory. Perhaps a new theory will be posited that will encompass the Big Bang, just as Einstein's relativity enclosed Newton's laws of gravity. As far as we now know, the Big Bang is completely consistent with all the data, and nothing else has ever come as close to describing how the universe is structured. ■

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Questions to Consider

1. What exactly is this famous cosmic microwave background? What makes it cosmic? What makes it microwave? And what makes it background?
2. What role does Einstein's general theory of relativity play in the Big Bang?

The Greatest Story Ever Told

Lecture 9

All the space and all the matter and all the energy of the known universe were contained in a volume less than one-trillionth the size of the point of a pin. That size is about the size of an atom.

This lecture synthesizes the greatest discoveries of physics, astrophysics, chemistry, and biology to present a coherent story of the birth and evolution of the cosmos. Modern humans are not the first group of people to speculate about cosmic evolution, but we are the first to use the tools of science to describe the birth of the cosmos, trace its progress, and understand our place in it. This lecture brings together all the branches of science to tell the story of our existence.

Before we begin, we must have a basic understanding of Einstein's famous equation, $E = mc^2$. This equation allows us to calculate the energy equivalent of the mass of a particle, such as a proton. We multiply the mass of a proton by the speed of light squared to arrive at the energy equivalent. This process also works in reverse. If you begin with a concentration of energy, you can use this equation to determine what kind of particles can be produced. The conversion of matter to energy and back again was rampant in the early universe and can be found today in particle accelerators. It no longer commonly occurs in the everyday world.

Twelve to 14 billion years ago, all space, matter, and energy in the known universe was contained in a volume less than one-trillionth the size of the point of a pin, or about the size of an atom. Conditions at that time were so hot that the basic forces of nature that collectively describe the universe were unified. Unification of forces is not a new concept. In the 19th century, electricity and magnetism, which had previously been thought of as two separate forces, were revealed to be two sides of the same coin. A theoretical formalism enabled us to see these two forces as one force manifested in different ways.

For reasons unknown, the point that contained all the universe began to expand. Black holes were spontaneously forming and disappearing out of the energy contained in the unified field. The energy density was so high that the result was not the formation of particles, but the formation of black holes. As we know, black holes are the curvature of space and time. The fabric of the universe reacts to the presence of black holes. If black holes are forming and unforming spontaneously in a small volume, the structure of space and time becomes severely curved and transforms into a spongy substance called *quantum foam*.

Quantum mechanics, which was developed in the 1920s to describe matter at its smallest scale, and Einstein's general relativity, the modern theory of gravity, do not intersect. These two theories operate in different domains. Even though these theories seem unrelated, they must have been unified when the universe was the size of an atom. As the universe continued to expand and cool, gravity split away from the other forces of nature. Next, the strong nuclear force and the electroweak force split from each other.

We believe that this splitting was accompanied by an enormous release of energy that had been stored in these merged fields. This energy forced a rapid expansion of the size of the universe equal to 10^{30} . This process is similar to a phenomenon that is observed in chemistry when water is frozen. The temperature of liquid water placed in a freezer will drop until it reaches a certain point when the water is converting itself to ice. After the liquid water is completely ice, the temperature will begin to drop again. At the point where the temperature is not dropping, the latent heat of the liquid water is being released.

The rapid expansion caused by the splitting of the fields stretched the cosmos. Much of the distinct variation in density and form of the universe became softened at this time. That smoothing of the universe is now down to 1 part in 100,000. Imagine creating a ripple in a 2-mile-wide lake. A ripple corresponding to the smoothness of the universe would be only an inch tall. When it formed, matter coalesced in the ripples, or fluctuations, in the universe. In the large-scale structure of the cosmos, the galaxies are in those ripples.

At this time in the evolution of the universe, the temperature was hot enough for photons, that is, particles of light, to spontaneously convert their energy into matter/antimatter pairs, such as a proton and an anti-proton. The result was a soup of matter/antimatter and photons, an interplay of particles forming, then annihilating, then re-forming. For reasons unknown, matter/antimatter symmetry was broken. One out of every billion photons that would normally convert itself into a pair made a single particle of matter. As the universe continued to cool, the energy level of the photons dropped below that required to create particles. What was left, then, was photons and

The energy density was so high that the result was not the formation of particles, but the formation of black holes.

matter particles. These particles are responsible for all the structures of matter that we know of in the cosmos, including stars, galaxies, and light.

The four separate forces that were unified in the early cosmos are the strong nuclear force, the electroweak force, electromagnetism, and gravity.

The strong nuclear force binds particles in the nucleus of the atom. Protons are positively charged and repel each other, but they exist together in nuclei. How? If the protons get close enough to each other, the strong force takes over and binds them together. The electroweak force is responsible for decay of nuclei. Electromagnetism is revealed in the bonding of atoms; this force keeps matter together. The force of gravity has the greatest impact on events in the cosmos.

The temperature 300,000 years after the Big Bang was 3000 degrees K. Until the universe reached that temperature, protons and neutrons were combining to make the lightest elements on the periodic table—hydrogen, helium, and lithium. Electrons were roaming free. The temperature was not cool enough for electrons to settle into atoms. When electrons and photons interact, light is scattered, which means that at temperatures hotter than 3000 degrees, the universe was opaque. Our telescopes today cannot see through that wall of light. At 3000 degrees, electrons became bound to atoms, and the universe became transparent. The photons, which have continued to cool, still exist in the universe as the cosmic microwave background.

In the first few billion years of the cosmos, 50 to 100 billion galaxies were formed, each containing up to 100 billion stars and each star undergoing thermonuclear fusion in its core. The pressure and temperature conditions in stars of more than about 10 times the mass of the Sun are great enough to create heavy element factories in their cores. These *supernovae* create carbon, nitrogen, iron, oxygen, and so on, then explode and scatter the elements throughout the universe. After about 7 or 8 billion years of this chemical enrichment of the universe, an undistinguished star was born—the Sun. The gas cloud that made the Sun had a big enough supply of heavy elements that it spawned a system of planets, tens of thousands of asteroids, and trillions of comets. The Earth spent the next 600 million years under heavy bombardment from the debris that was left over after the formation of the solar system. The asteroids pounding Earth raised the temperature high enough to render the planet sterile. Earth had the ingredients for life, but nothing could form.

When the bombardment subsided, Earth's surface cooled, and complex molecules began to form in the chemically rich liquid of the oceans. Two hundred million years elapsed from the end of the period of heavy bombardment to the point of Earth's oldest fossils, dating to about 3.8 billion years ago. The earliest life forms were single-celled anaerobic organisms. They thrived in an atmosphere of carbon dioxide and released oxygen as a waste product. The release of O_2 enabled a population of aerobic creatures to take over Earth. The release of O_3 enabled the formation of the ozone, which protects us from the ultraviolet radiation of the Sun. We owe the remarkable diversity of life on Earth to one element, carbon. Carbon is plentiful in the universe and can make more kinds of molecules than all the other elements combined.

As we've learned, though, life is fragile. An asteroid hitting Earth could change the entire ecosystem and cause the extinction of 70 percent of the species of life on the planet. Of course, such an event occurred 65 million years ago, causing the extinction of the dinosaurs. That occurrence, in turn, opened up a new ecological niche for the survival of mammals. One branch of mammals became primates, which evolved into homo sapiens. That life form invented the methods and tools of science with which to deduce the origins and evolution of the universe. This progression tells us that we are

not *in* the universe but *of* it. We are born from the universe, and we have been empowered to learn about it and figure it out—and we've only just begun to do so. ■

Suggested Reading

Anonymous. *The Bible According to Einstein*. New York: Jupiter Scientific Publishing Co., 1997.

Schulman, Eric. *A Briefer History of Time*. New York: W.H. Freeman & Co., 1999.

Questions to Consider

1. What areas of profound ignorance remain in the greatest story ever told?
2. What was so important about the first three or four minutes of the universe?

Forged in the Stars

Lecture 10

It is true that with some elements, if you give them one neutron they go unstable and they kick the whole neutron out again. But if they have two neutrons, they are stable and given time they will convert the neutrons to protons.

This lecture highlights one of the most important discoveries in any field in the 20th century: the origin of the elements that make up life. Despite its importance, however, most people aren't aware of this discovery. Our understanding of the formation of elements did not come from the common picture that we might think of: a lone genius working night and day in a laboratory until he or she reaches a "Eureka!" moment. Instead, this discovery took place over many decades and involved many people and complicated concepts. For this reason, the discovery is hard to condense for the media and remains outside of our everyday awareness.

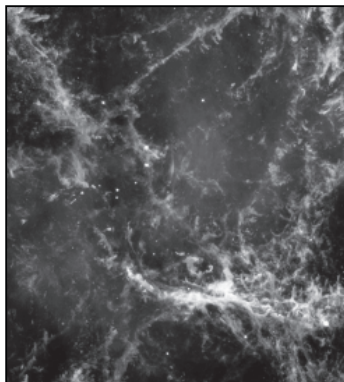
Elements in the cosmos have two primary origins: All the hydrogen and most of the helium in the universe came from the Big Bang; the heavier elements are formed in the centers of stars. As mentioned earlier, a supernova is a variety of star that has a high enough mass to create the conditions to manufacture elements. If we study supernovae, we learn how they manufacture elements and distribute these elements in the galaxy. This knowledge, in turn, teaches us about the relative mix of elements found in the universe.

In 1957, a seminal research paper was published that brought together data from different branches of science to reveal supernovae as the primary source of the existence of heavy elements in the galaxy. This paper, "The Synthesis of the Elements in Stars," was written by Margaret and Geoffrey Burbidge, along with William Fowler and Fred Hoyle. For 40 years before 1957, scientists had wondered whether the source of energy in the stars could be responsible for transmutation of the elements. It was not until this time, however, that enough experimental data was accumulated to confirm that theory.

The results of this paper were driven by a number of “messy” questions. How do the various elements on the periodic table behave when subjected to extreme pressures and temperatures? This question must be answered primarily on the basis of the laws of physics. Scientists cannot do much experimenting to discover these behaviors. Are elements formed through fusion or fission? Which process predominates? Are these processes easy or difficult? Does a certain reaction produce energy (*exothermic*) or reduce energy (*endothermic*)? How can we explain the periodic table? Can we start with hydrogen and helium—the birth ingredients of the universe—and manufacture all the other elements?

These questions were basic in the attempt to understand the formation of the elements, but there is another question that is almost impossible to answer from first principles: What are the collision cross-sections of the nuclear pathways? In other words, if we want to engineer a collision between two particles, how big a target do these particles represent to each other? Are they, in fact, very small and, thus, our aim must be precise, or do they somehow take up more space and become more likely to hit each other? In atomic physics, researchers need to know the likelihood and rates at which elements will collide. The wrong cross-section calculations will result in the prediction of different kinds of reactions that would never take place.

Sir Arthur Eddington had thought about these questions at the turn of the century. His book *The Internal Constitution of the Stars* put forth the idea that the stars were the “crucibles” in which the lighter atoms were formed into more complex elements. Eddington knew that an exotic environment with very high temperatures was required to force light elements to collide and make heavier elements. However, he was missing a piece of physics needed to figure out the whole story.



The Crab Nebula.

Hubble Heritage Team (STScI/AURA/NASA) using data collected by W. P. Blair (JHU), K. Davidson (U. Minn.), R. A. Fesen (Dartmouth), A. Uemoto (JHU), G. M. MacAlpine (U. Mich.) and R. B. C. Henry (U. Okla.).

In the 1920s, with the development of quantum mechanics, the missing piece was supplied. If we consider bringing together two hydrogen nuclei, we know that their two protons will repel each other under normal circumstances. We need to heat the gas so that the particles will move faster and get closer together. If we can get these particles close enough, the strong nuclear force will take over and they will bind. The particles must cross the *potential barrier*, that is, the electromagnetic resistance of the two positive charges.

Eddington calculated the temperature of the center of a star at about 10 million degrees. Then, he calculated the temperature required for protons to collide with enough speed to bind together. That temperature is about a billion degrees. It seems obvious that elements could not be formed in stars at 10 million degrees, but we knew that the hottest place in the galaxy was the center of a star. If elements weren't formed there, then where else? We now know that the speed of protons at 10 million degrees is sufficient to make them collide, but not in the traditional way that we might think.

The collision of protons at 10 million degrees is possible through a phenomenon in quantum mechanics that has no analog in everyday life—*tunneling*. Think of rolling a toy truck up a hill. Under normal conditions, you would have to roll the truck up the hill at a certain speed for it to reach the crest and go over. In quantum mechanics, under certain conditions of temperature and pressure, if you roll the truck up the hill, a tunnel will open in the hill and the truck will pass through to the other side. Thus, in trying to overcome their repulsion, some protons do connect at temperatures as low as 10 million degrees. Before quantum mechanics, however, we had no way to know this.

Next we might ask about the relative amounts and distributions of elements in the universe. In 1931, Robert Atkinson published a paper about what goes on inside of stars. He tried to show how the elements were built up one by one and how this process accounted for their relative distributions. Once again, Atkinson did not get the full answer because he was missing a piece of the puzzle—the neutron—which was discovered a year later by James Chadwick.

Because neutrons have no charge, they can be used to build up the count of particles inside the nucleus. There is no resistance to the addition of neutrons and no change in the species of the nucleus when neutrons are added. In other words, a hydrogen atom is still hydrogen with the addition of neutrons, but it becomes an *isotope*, an element with varying numbers of neutrons and the same number of protons. Some elements reject the addition of extra

[Burbidge, Fowler, and Hoyle's] conclusions might be summarized by noting that we—human beings—are made of star dust.

neutrons. In an atom of such an element, the added neutron is spontaneously transformed into a proton that releases an electron. A new proton, then, has joined the nucleus. This process is an effective way of building up elements.

This process varies in different elements, but it leads to an understanding of the formation and distribution of elements in

the universe. The final piece of this puzzle was the collision cross-sections, most of which came out of the research that went into the Manhattan Project. We now knew how elements were made in the centers of high-mass stars.

How are these elements distributed in the universe? Thermonuclear fusion takes place in the cores of high-mass stars. Such a star begins by fusing hydrogen into helium, which results in a loss of mass. The mass is converted, according to $E = mc^2$, into an enormous amount of energy. This process continues as the star fuses helium into carbon, carbon into oxygen, oxygen into neon, and so on. The star is receiving energy at every phase, but it is not as efficient; it begins to burn through these heavier elements very quickly.

As the fusion process moves up the periodic table, it reaches iron. The star will collapse a little bit to increase its temperature and begin to fuse iron. Extremely high temperatures are required for this fusion. The fusion of iron absorbs energy—it doesn't release energy. However, the creation of energy supports the star from collapse; without a source of energy, the star has nothing to hold itself up. It destabilizes and collapses in a matter of hours. The collapse of the star rebounds from the center in a titanic explosion that we call supernovae. These are visible across the galaxy and spew a trove of enriched chemical elements throughout the universe. The remnant of one

such supernova is the Crab Nebula, a star that exploded and was recorded by the Chinese on July 4, 1054 A.D.

The 1957 paper of Burbidge, Burbidge, Fowler, and Hoyle combined the tenets of quantum mechanics, the physics of explosions, the latest collision cross-sections of atomic nuclei and resulting nuclear pathways, and basic stellar evolutionary theory to account for the existence, distribution, and relative abundance of elements in the cosmos. Their conclusions might be summarized by noting that we—human beings—are made of star dust. ■

Suggested Reading

Althshuler, Daniel R. *Children of the Stars*. Cambridge: Cambridge University Press, 2002.

Spitzer, Lyman. *Searching Between the Stars*. New Haven: Yale University, 1982.

Questions to Consider

1. Where do all the heavy elements in the universe come from?
2. Describe two reasons why carbon is so useful to life.

The Search for Planets

Lecture 11

There are 100 billion stars in the galaxy, and in the whole universe there's about 50 to 100 billion galaxies. You take those two numbers and multiply them and that gives you the total number of ordinary stars. That's a one followed by 21 zeros, one sextillion.

It seems fairly obvious that planets outside our solar system would be found in the Milky Way, but before the 1990s, our planets were the only ones known in the galaxy. Now, we know about at least 100 planets outside the bounds of our solar system. Astrophysicists did not look for these planets just out of curiosity but as part of a systematic search for other planets that could support life. This lecture discusses the tools and methods used to find other places in the universe that might be hospitable to human life.

Given that our Sun is just an “ordinary” star, and it has enabled the life of our species, we might wonder if other “ordinary” stars can also support life. We can find the total number of possible stars that might support life by multiplying the number of stars in a galaxy (100 billion) by the number of galaxies in the universe (50–100 billion). The result is 1 sextillion, or a 1 followed by 21 zeroes. That number is 100,000 times larger than the total number of sounds uttered by all human beings who have ever lived. Each of those stars could have at least one orbiting planet that is capable of supporting life.

How do we go about finding these planets? We can't just look up in the sky and find a likely planet, because a planet is usually in orbit around a host star that is much greater in brightness. A planet might be 1/100,000,000 the brightness of its host star. Astrophysicists needed to find some methods to block the light of the host stars. Many planets, as well as solar systems in formation, give off principally infrared light as opposed to visible light. Using an infrared telescope, we might increase the brightness of a planet to 1/10,000,000 that of its host star. Within the optics of the telescope, an eclipsing disk can also be added to block the light of the host star. Using

this method, researchers in the 1980s discovered an orbiting planet in a solar system in formation around the star Vega, one of the brightest stars in the night sky. Close examination of Vega revealed infrared emission surrounding the star. Even closer analysis enabled us to see craggy chunks of rock and dust still in the act of forming a system of planets.

To find planets that are capable of supporting life, we need to look for Sun-like stars and stars that are not in multiple-star systems. Most stars in the sky are in multiple-star systems, but planets in orbit are not stable in the changing gravitational field of these systems. These planets are often jettisoned into interstellar space and become *vagabond planets*. We need to look for single stars with stable orbits.

We might have many views in the galaxy of a single host star with a planetary system. For example, we might be able to look down on such a system for a bird's eye view. What we need to find, however, is an edge view.

In an edge view, a large planet, similar to Jupiter, for example, will orbit around and move in front of the host star. This orbit will not totally eclipse the star, but it will block some of the star's light. We can monitor that star's light output. If it is normally stable but is blocked with some regularity, we know that a planet is in orbit around the star. In other words, we look for regularly occurring variations in the light of an object that might otherwise be stable. We need to be careful in drawing conclusions from this method of observation because there is a possibility that the star's light is being blocked by another phenomenon, such as sunspots.

Another method for finding planets is called *microlensing*, which taps into the theory of general relativity. General relativity states that the fabric of space and time warps in the vicinity of a source of gravity. A vagabond planet moving in front of a star can have an effect on the star other than blocking its light. The gentle curvature of space around the planet may be just enough to bend and focus the paths of light emanating from the star from different directions in the cosmos. As the planet drifts across our view, the

To find planets that are capable of supporting life, we need to look for Sun-like stars and stars that are not in multiple-star systems.

starlight greatly increases in brightness, then drops off. The planet's gravity serves as a lens to focus the light of a distant star behind it. This method of finding planets has its drawbacks. First, it is non-repeating; the planet drifts past the star only once. Second, the likelihood of a planet crossing the view of a star is exceedingly low.

A tried-and-true method for discovering planets is by using the Doppler effect, discovered by Christian Johann Doppler, a German physicist, in the 19th century. Doppler noticed the difference in pitch of a train whistle as a train approached, then receded. He found the mathematical formula that calculated the rate that the frequency changes. This frequency change is a basic property of sound waves emanating from an object in motion; the same property also holds for light waves. We usually think of planets orbiting around a star in the center, but this view is not completely realistic. In fact, the star and the planet are both orbiting around their common center of gravity, which is generally not at the center of the star. Thus, we can measure the change in the frequency of the light as the star approaches and recedes. The change in frequency is the same as the change in wavelength.

In other words, the host star is moving in reaction to the orbit of the planet, and the movement of the star has the same period as the movement of the planet. The amount of the star's motion is also a function of the mass of the planet. The bigger the mass of the planet is, the greater the motion of the host star. Using this method, we can also find not just one orbiting planet but multiple planets. We can see more than one level of variation in the movement of the host star.

The first planets discovered using this method were the size of Jupiter. Obviously, we would expect to find large planets having a greater effect on the movement of the host as opposed to small planets, such as Earth, which would have a smaller effect on the host. These large planets were also orbiting very close to their host stars, where we would never have imagined we would find them. Our assumption was that rocky planets would be close to the host, while massive gaseous planets would be farther out, similar to our solar system. Thus far, we have not seen that kind of system and have had to change our theories of planet formation. Our methods may be preventing us from seeing other planetary systems accurately. It is possible,

for example, that we have not been using this method long enough yet to establish a baseline to measure a full orbit of another solar system that might have a very distant, massive planet. Such a planet may take 8–20 years to complete an orbit, and we have been using this method for only about 10 years. In a star system in formation, a massive planet may move close to the host star by flinging debris out of its way as it migrates in.

Will we ever find any planets to visit? If we were able to travel 1000 miles per second—100 times faster than any human has ever traveled—it would take us 800 years to reach the closest star to the Sun, which doesn't have any known planets. We would need 2000 years to reach a star that we know has planets. NASA has plans to build a Terrestrial Planet Finder (TPF) and combine it with the Space Interferometry Mission (SIM). The result will be a bank of telescope dishes working in harmony to provide the sharpest possible images of the smallest possible objects in the universe.

What we want to see is an Earth-like planet, its oceans, atmosphere, and so on. We would use spectrographs to measure the chemistry of such a planet's atmosphere, which is a product of what's happening on the surface. The discovery of oxygen in a planet's atmosphere, for example, would be evidence of metabolism on the planet. A spectrograph might also detect CFCs, the destroyers of ozone, or hydrocarbon contaminants, the product of global deforestation. Such discoveries would be sure signs that the planet does not have intelligent life. ■

Suggested Reading

Dorminey, Bruce. *Distant Wanderers: The Search for Planets Beyond the Solar System*. New York: Springer-Verlag, 2001.

Questions to Consider

1. What is the Doppler shift, and why is it so useful for discovering exo-solar planets?
2. Among the first hundred solar systems discovered, how do they compare with our own? How are they similar? How are they different?

The Search for Life in the Universe

Lecture 12

Clearly, if you're going to imagine life somewhere other than Earth, you imagine it on a planet, not somehow living inside a star. The discovery of planets fueled that curiosity and that act of having found planets—now that number rising through 100; more planets known outside of our solar system than within it—the prospects of finding life dramatically increased, just by the fact of this knowledge.

No question looms larger in the minds of the public than “Are we alone in the universe?” We don't know the answer, but we certainly have enough information to engage in a fertile discussion of the topic. In the early 1990s, when we started discovering planets beyond our solar system, the prospect of finding life dramatically increased and interest in this question was renewed. We close this series of lectures by examining the very real possibility that life exists elsewhere in the cosmos and speculating about its origins and chemical makeup.

On Earth, life teems everywhere, but is it presumptuous to assume that such fertility exists elsewhere in the universe? Even if the ability to support life is rare, the universe is so vast that we have a huge area to sample and an extraordinary number of possibilities. As we said, the cosmos contains 1 sextillion stars, each of which could have planets. There are more stars in the universe than grains of sand on all the beaches on Earth. It would be egocentric to presume that we are alone in the cosmos, even if life is exceedingly rare.

The anthropic assumption that human beings are somehow special has misled people for generations and reversed the progress of science. In the early 1500s, Nicholas Copernicus, in his book *De Revolutionibus*, established the *Copernican principle*: that the Sun is in the center of the known universe, instead of the Earth. He asserted that Earth was no more important than the other planets in the solar system, nor was the Sun a particularly important star.

Copernicus was not the first thinker to make this assertion. In the 3rd century B.C., the Greek philosopher Aristarchus also speculated that the Sun was in the center, but his idea never caught on. The geocentric view of the universe made its way into the teachings of Aristotle and, later, the Catholic Church. We now know that we're not even in the center of the Milky Way, nor is the Milky Way in the center of the universe, even though all other galaxies seem to be receding from us. We learned from Einstein that no matter where we look in the universe, galaxies will seem to be receding from that point.

What can we learn from the biodiversity of life on Earth? The range of life forms on Earth is extraordinary. Think, for a moment, of the following random list of life forms: rhinovirus, algae, beetles, sponges, jellyfish, snakes, condors, and giant sequoia. Add to this list trilobites, which ruled the planet 500–600 million years ago, and dinosaurs. It's hard for us to believe that all these life forms come from the same universe, much less the same planet. Imagine describing a snake as an alien life form: Many snakes stalk their prey with infrared detectors. They are capable of swallowing prey that is five times the size of their heads. They have no arms, legs, or other appendages, but they can slide along the ground at a rate of 2 feet per second. Such a creature is a good candidate for an alien, yet it exists here on Earth.

Hollywood is embarrassingly unimaginative in its portrayal of the diversity of aliens. Most of its creations have arms, legs, heads, fingers, and so on. These aliens are basically identical to humans, especially compared to the array of life forms listed above. Life on other planets should look as different compared to humans as other life forms on our planet look in comparison. Note, however, that we have DNA in common with every life form on Earth.

What do we know about the science, or chemistry, of life? We know that life forms on Earth are based on organic chemistry, and a key ingredient of organic chemistry is carbon. We are carbon-based life. Carbon is produced in vast quantities inside of stars and released into the galaxy, enriching clouds that then collapse and form stars, planets, and ultimately, people. Chemically, carbon combines in more ways to make more kinds of molecules than all other molecules that exist. If you were to pick an element on which to base the diversity of life, carbon is the prime candidate. Life, which is opportunistic, relies heavily on the fact that carbon can bond with

itself and other elements in many ways, including ways that we are still discovering. Carbon is so versatile and plentiful that we can state with a good deal of certainty that other life in the universe will probably be based on carbon chemistry.

Also abundant in the cosmos and in humans are hydrogen, nitrogen, and oxygen. We owe the abundance and distribution of these ingredients to the remnants of stars that have exploded, such as the Crab Nebula, a nebulosity formerly contained in a star that blew up 2000 years ago. The Crab Nebula is still expanding into space. Each of the color variations we see in images of this nebula represents a different chemical species manufactured in the thermonuclear crucible that was once the center of this star. Without these heavy elements, which are still traveling through the cosmos, the formation of planets with any ingredients other than those that were products of the Big Bang would be impossible.

How special is life on Earth? We've all seen lists of the chemical ingredients of human life. We know that the human body is 80 percent water and, therefore, it contains more hydrogen atoms than anything else. Next in order comes oxygen, carbon, nitrogen, and so on. The same list of ingredients for the universe would match one for one with those in the human body. First in the universe is hydrogen, followed by helium, which is inert; it has no chemical utility. These are followed by oxygen, carbon, and nitrogen. The conclusion is that humans are *of* this universe. If we were made of extremely rare ingredients in the universe, we might have an argument for our uniqueness, but that is not the case.

Where should we look for another planet that might have life? Life as we know it requires liquid water. We don't know if that is a universal need. Originally, we looked for planets that might sustain life in a certain habitable zone, not too close or too far from their host stars.

We have since had to expand the habitable zone, because of observations from Europa, a moon of Jupiter. The surface of Europa appears to be frozen, but it experiences stresses from the tidal forces of Jupiter and its 20–30 satellites. Those stresses impart heat into the interior of Europa, which seems to be melting the ice in some places and causing shifting patterns in the

ice on the surface. We believe that Europa has an ocean that has been in existence for a billion years. Life on Earth achieved major advances in our oceans. If we're looking for other life in the universe, we might need to start the search in our own backyard.

Mars shows evidence of the past existence of running water. We can see dried riverbeds and flooded plains, as well as evidence that some kind of material was carried in these flood waters, but there is no sign of life on Mars now. What happened to the water and atmosphere of Mars? We don't know. The water could be subterranean now, under the permafrost. If Mars once had running water, it may once have had life. Any expedition to Mars should include a geologist and a paleontologist to search for fossils.

Note, however, that we have DNA in common with every life form on Earth.

Of course, the ultimate question about other life in the cosmos is, what is the chance that alien life is intelligent? A few years ago, a rock was found in Antarctica thought to be from Mars and showing evidence of single-celled life. Something big, such as an asteroid, must have hit Mars a long time ago, and pieces of its material were thrust out into space. Perhaps Mars, with its wet history, formed life before life on Earth. If so, perhaps that single-celled life stowed away on a rock that landed here 4 billion years ago. If that's true, then all life on Earth has a Martian origin. This idea is called *panspermia*. If life on Mars had DNA, we won't know whether DNA is an inevitable molecule of a chemical soup or whether we got our DNA from Martians in the first place.

One way to think about these questions is the *Drake equation*, attributable to American astrophysicist Frank Drake. This equation is not a typical mathematical formula, but a sequence of probabilities that affect the search for life. First, we ask, what percentage of stars lives long enough for life to evolve? Then we ask, of those stars, what percentage has planets? Of those planets, what percentage is in the habitable zone? Of those in the habitable zone, what percentage gave birth to life? Of those that have life, what percentage evolved life to intelligence? Of those that evolved intelligent life,

what percentage developed technology that would enable civilizations to communicate across the galaxy?

To “solve” this equation, we set up the probabilities, then multiply them out to arrive at the number of possible civilizations with which we might communicate. We may need to modify some of the terms of this equation since its development. As we said earlier, the habitable zone seems to be broader than we originally imagined. Further, we know that life can thrive based on geochemistry rather than on energy from the Sun; this is revealed in the life forms that exist deep in the ocean, in boiling water heated by magma from the center of the Earth. The number of places we can find life and the hardiness of life are greater than what Drake imagined.

If we find other intelligent life, how will we communicate with it? We can’t travel to other likely planets, because they are simply too far away, but we can send out radio waves, which travel at the speed of light. The language we use for these communications is mathematics. The duration of technology is a factor in communication in the cosmos. Suppose alien signals arrived on Earth 100 years ago. The aliens would assume that no intelligent life existed here, because we had no way to respond to their signals. We have been technologically capable of responding for only the last 50–75 years out of 4.5 billion. We have been communicating with the galaxy unwittingly for the past 60 years by sending out television signals. Alien anthropologists may now be decoding the *Howdy Doody Show*, *Amos and Andy*, and *I Love Lucy* as the earliest signs of intelligence on Earth.

As we conclude these lectures, I hope “my favorite universe” has now become “your favorite universe.” I will leave you with this thought: “In life and in the universe, it is always best to keep looking up.” ■

Suggested Reading

Goldsmith, Donald, and Tobias Owen. *Search for Life in the Universe*. Mill Valley, CA: University Science Books, 2001.

Margulis, Lynn, and Dorian Saga. *What Is Life?* New York: Simon & Schuster, 1995.

McKay, D. S., et al. *Search for Past Life on Mars*. Washington, DC: American Association for the Advancement of Science, 1996.

Questions to Consider

1. In what fundamental way do Hollywood aliens show a deep lack of imagination?
2. Silicon and carbon are chemically similar, yet life as we know it is based on carbon. Describe two reasons why carbon is so useful to life and why silicon-based life may be much rarer than carbon-based life.

Timeline

Age

0 (13.5 billion years ago)	Big Bang; the space, time, matter, and energy of our universe burst forth into existence from a small, dense, hot fireball.
Before 10–43 seconds	Planck era; quantum foam prevails; space and time are entangled; all forces of nature are merged.
10–43 seconds	Gravity separates and becomes distinguishable from other forces of nature.
10–36 seconds	Strong nuclear force becomes distinguishable from electroweak forces, triggering a period of rapid inflation.
10–32 seconds	Inflationary era ends; era of quark formation begins.
10–12 seconds	Split of electromagnetic and weak forces, leaving the four familiar forces of nature.
10–6 seconds	Quark-hadron transition, where quarks combine to form protons, neutrons, and other baryons.
0.02 seconds	Formation of electrons and positrons.

3 minutes.....	Expanding, cooling universe “freezes” out 86% protons and 14% neutrons.
35 minutes.....	Less than 1 in 10 ⁸ excess of electrons over positrons leaves a universe in which matter dominates over antimatter.
380,000 years	Remaining free electrons combine with nuclei. Universe becomes transparent to light. Distribution of matter at this moment leaves a signature in the pattern of photons, measured as the cosmic microwave background.
20 million years.....	Era of the first stars in the universe.
3 billion years.....	Birth of Milky Way galaxy.
8 billion years (4.6 billion years ago).....	Birth of solar system. Period of heavy bombardment begins, raining leftover debris from interplanetary space on the existing planets.
4.0 billion years ago.....	Period of heavy bombardment ends.
5000 years ago	Stonehenge built; as a monument to the cycle of the seasons, Stonehenge is regarded as one of the first astronomical observatories.

Date

384–322 B.C.	Aristotle, Greek philosopher; advanced the idea of the geocentric (Earth-centered) universe.
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- 310–230 B.C. Aristarchus of Samos, Greek astronomer and mathematician; first proposal of a heliocentric (Sun-centered) universe.
- c. 85–165 C.E. Claudius Ptolemy, Greek astronomer and geographer; perfected the geocentric universe with a full system of epicycles depicting the cyclic movement of all astronomical bodies around the Earth.
- 476 C.E. Fall of the Roman Empire.
- 500–1000..... Dark Ages in Europe. Plague ravages population; witches burned; heretics disemboweled.
- 900–1100..... Baghdad is the world’s center of learning and scholarship in astronomy, mathematics, medicine.
- 1473–1543..... Nicolaus Copernicus, Polish astronomer; on his deathbed, he publishes *De Revolutionibus*, containing a fertile prescription for a heliocentric universe.
- 1546–1601..... Tycho Brahe, Danish astronomer; measured planetary positions with unprecedented accuracy from his observatory.
- 1564–1642..... Galileo Galilei, Italian physicist and astronomer; father of modern science in methods, tools, and philosophies.

- 1571–1630..... Johannes Kepler,
German mathematician.
- 1600..... Giordano Bruno, Italian monk and
astronomer, burned alive, naked and
upside down, by the Catholic Church,
for suggesting that Earth was not alone
in the universe as a habitat for life.
- 1608..... Hans Lippershey, Dutch spectacle
maker, invents telescope.
- 1609..... Galileo makes his first telescope. A year
later, publishes *Sidereus Nuncius* (*The
Starry Messenger*), reporting on his
observations of the heavens, the first
ever with a telescope, containing proof
that Earth is not the center of all motion.
- 1609..... Kepler publishes his first two
laws of planetary motion based on the
data acquired and willed to him by
Tycho Brahe.
- 1619..... Kepler publishes his third law of
planetary motion, the first predictive
mathematical statements about the
behavior of the universe.
- 1632..... Galileo publishes *Dialogue Concerning
the Two Chief World Systems*, a staged
debate between the heliocentric and
geocentric theories, mocking believers
of the geocentric system.

- 1633..... Galileo faces the Holy Roman Inquisition, is forced to recant, and is placed under house arrest.
- 1643–1727..... Isaac Newton, English physicist; most brilliant and influential scientist ever to have lived.
- 1687..... Newton publishes *Principia Mathematica*, containing the universal laws of motion and gravity.
- 1704..... Newton publishes *Optics*, containing laws of optics that demonstrate that white light is composed of colors and advancing the idea that light travels in particles rather than waves.
- 1776..... American Revolution.
- 1789..... French Revolution.
- 1795..... France advances and officially adopts the metric system.
- 1799–1805..... Marquis de La Place, French mathematician, publishes the five-volume *Mécanique Céleste*, extending the power of Newton’s theory of gravity.
- 1855–1856..... James Clerk Maxwell, English physicist, advances his famous equations that describe the complete behavior of electromagnetic energy, creating a foundation for Einstein’s relativity theories.

- 1895..... Joseph John Thompson, English physicist, discovers electron.
- 1900..... Max Planck, German physicist, introduces the *quantum*, ushering in the era of modern physics.
- 1905..... Albert Einstein, German physicist, publishes “On the Electrodynamics of Moving Bodies,” commonly known as his special theory of relativity, redefining our understanding of the relationship between space and time.
- 1916..... Einstein publishes his general theory of relativity, a modern theory of gravity that supplants Newton’s universal laws of gravitation. Describes a universe in which space tells matter how to move, and matter tells space how to curve. Allows for the existence of black holes and the Big Bang.
- 1918..... World War I ends.
- 1918..... Ernest Rutherford, New Zealand physicist, discovers the proton.
- 1919..... Arthur Stanley Eddington, English astrophysicist, measures the bending of starlight around the Sun, confirming a basic prediction of Einstein’s general theory of relativity.
- 1920s..... Quantum mechanics developed by many physicists in America and several European countries.

- 1923..... Edwin Hubble, American astronomer, discovers distance to Andromeda nebula. It is a galaxy external to the Milky Way.
- 1929..... Hubble discovers expanding universe.
- 1932..... James Chadwick, English physicist, discovers neutron, completing our basic picture of the atomic nucleus.
- 1933..... Carl David Anderson, American physicist, discovers the positron, the first antimatter particle and the favorite fuel of science fiction writers.
- 1945..... World War II ends. America detonates three atomic fission bombs, one as a test and two in warfare against Japan.
- 1957..... American astrophysicists Margaret E. Burbidge, Geoffrey R. Burbidge, and William A. Fowler and English astrophysicist Fred Hoyle publish the landmark paper “Synthesis of the Elements in Stars,” describing in detail, for the first time, the formation of heavy elements inside of stars via thermonuclear fusion. Calculations made possible by declassified military documents on nuclear energy.
- 1957..... Soviet Union launches *Sputnik I*, the first artificial satellite. It is thrust into orbit based on the principles of gravitation first advanced by Newton.

- 1961..... Yuri Gagarin, Soviet cosmonaut, becomes the first human to orbit around Earth.
- 1963..... Martin Schmidt, American astrophysicist, discovers quasars, galaxies whose prodigious energy output is driven by supermassive black holes lurking in their cores and dining upon matter that comes too close.
- 1965..... Arno Penzias and Robert Wilson, American physicists, discover the cosmic microwave background, formed 380,000 years after the Big Bang and permeating the expanding universe as a bath of microwave light.
- 1966..... NASA's *Gemini* program releases an image of Earth from space.
- 1968..... NASA's *Apollo* program releases an image of "Earth Rise" over the lunar landscape.
- 1969..... Neil Armstrong and Buzz Aldrin, American astronauts, are the first to walk on the Moon.
- 1976..... NASA sends two unmanned *Viking* spacecraft to visit Mars. They look for life but find none.
- 1990 NASA launches the Hubble Space Telescope, the first of the great spaceborne observatories, giving unprecedented clarity of cosmic imagery.

- 1994..... Comet Shoemaker Levy-9 collides with Jupiter, acting as a shot across our bow and reminding Earthlings of the hazards of asteroid and comet impacts.
- 1995..... Michel Mayor and Didier Queloz, Swiss astrophysicists, discover the first planet in orbit around a star other than the Sun.
- 1996..... NASA releases the “Hubble Deep Field,” the deepest image of the universe ever taken, showing countless galaxies with remarkable detail.
- 1996..... Martian Meteorite ALH84001 shows possible evidence for life on Mars.
- 1999..... American astronomer Brian Schmidt and others use light from distant supernovae to discover that the expansion of the universe is accelerating; this discovery implies the existence of a dark energy supplying a form of antigravity in the vacuum of space.
- 2002..... More than 100 planets are now known in orbit around stars other than the Sun.
- 2003..... NASA’s Wilkinson Microwave Anisotropy Probe measures the cosmic microwave background with unprecedented accuracy and precision, confirming the basic tenets of Big Bang cosmology.

Glossary

accretion disk: A swirling disk of gas that funnels down toward a neutron star or black hole and is drawn from a nearby star or clouds in interstellar medium.

air resistance: The resistance and subsequent slowing experienced by a moving object as its surface encounters air molecules.

antimatter: The complete opposite of regular matter. Antimatter has the reversed characteristics of regular matter; for instance, the electrical charge and spin of regular matter is completely reversed in an antimatter particle.

asteroid belt: The region between Mars and Jupiter that is littered with chunks of rock and iron debris left over from the formation of our solar system.

asteroids: Sometimes called minor planets, asteroids are chunks of rock and iron left over from the formation of the solar system. Some are the remains of shattered mini-planets. Although asteroids can be found on almost any orbit around the Sun, most orbit in the gap between Mars and Jupiter, an area known as the *asteroid belt*.

astrophysics: The branch of science that seeks to apply the laws of physics to explain the past, present, and future of the universe and all its content.

atmosphere: The gaseous envelope surrounding a planet.

atmospheric pressure: The weight of a column of air that is the height of the atmosphere. Expressed as the ratio of force and area, as in “pounds per square inch.”

atom: The smallest part of a chemical element that retains the identity of the element. It is normally composed of electrons, protons, and neutrons.

aurora: Curtains of lights in the upper atmosphere created by charged particles from the Sun interacting with Earth's magnetic field and molecules in Earth's atmosphere. Earth's aurorae are commonly known as the Northern and Southern Lights. Scientists have witnessed auroras on other planets in our solar system, such as Jupiter and Saturn.

Big Bang: A theory for the origin of the universe that has achieved broad support from experiments in nuclear physics and observations in astrophysics. Its basic premise is that the universe began in a small, dense, hot state followed by an explosion that brought space and matter into existence approximately 13 billion years ago. The universe, today, still expands from this explosion.

binary stars: Two stars that form together and revolve around a common center of mass. As many as 50 percent of all star systems may be binary star systems.

black holes: Regions of space and time where the gravity is so high that the fabric of space-time itself has warped back on itself, preventing escape by anything that falls in or tries to get out. The escape velocity of a black hole is effectively greater than the speed of light.

blue shift: The shortened wavelength of light due to the motion of the light-emitting object toward you. Because motion is relative, this shift also occurs if you are in motion toward the object.

celestial: Related to the starry sky as seen from Earth.

centrifugal force: The outward force that an object feels when it revolves around any other object or position. It may also be considered the force that creates the tendency to "fly" off at a tangent. A centrifugal force is not a true force at all. It is just the tendency for the revolving object to move in a straight line—which is what the object would do if no force (like gravity or a tether) were acting to keep it revolving.

centripetal force: The force that keeps an object revolving around any other object or position. The Sun's gravity provides the centripetal force that keeps all planets in orbit. Otherwise, they would fly away into interstellar space.

chemical bonds: Bonds that enable atoms, by way of their outer electrons, to combine to form molecules.

comet: A comet is often referred to as a "dirty snowball." Comets are made of mostly ice and dust and orbit the Sun primarily in a flattened region of the solar system beyond the orbit of Neptune, known as the Kuiper Belt, and a spherical region that extends halfway to the nearest stars, called the Oort Cloud. A comet's "tail" is formed when the icy comet, approaching the Sun, evaporates its outermost layers and encounters the solar wind blowing the gasses into an extended stream away from the Sun, no matter what the comet's trajectory.

complex molecules: Ensembles of atoms, bound together into large molecules, such as proteins and nucleic acids, the building blocks of life.

constellation: The random patterns of stars in space as seen from the Earth. The celestial sphere is segmented into 88 constellations. Each constellation has a name that, in rare cases, actually resembles the assigned star pattern.

corona: The thin and vacuous outer atmosphere of the Sun, with a temperature of millions of degrees. Because it is considerably dimmer than the visual surface of the Sun, the Sun's corona can be detected only with specially designed telescopes called *coronagraphs* or during a total solar eclipse.

cosmic microwave background: An omni-directional bath of microwave energy with a temperature of a few degrees Kelvin. The cosmic microwave background is a residual signal from the early formation of the universe, when free but obscuring electrons combined with atomic nuclei, allowing light to travel freely. This signal lends strong support to the theory that the Big Bang is responsible for the expanding universe.

cosmic object: An object that resides in the cosmos or universe.

Cretaceous-Tertiary boundary: The geologic boundary between the Cretaceous and Tertiary periods in the fossil record of Earth history, dated to 65 million years ago and commonly called the *K-T boundary*. This important moment in time is characterized by an abrupt extinction of land animals and is believed to be the result of the impact of a large meteorite. This most famous of Earth's extinction periods left all classical dinosaurs extinct.

cubic inch, cubic centimeter, cubic foot, etc.: These units of volume can be remembered because a cube has volume—so that a “cubic” anything is the volume measured using a certain unit to multiply the length, width, and height.

dark energy: The universe contains a mysterious anti-gravity pressure that is responsible for the acceleration of the expanding universe in which we live. It may be associated with the vacuum of space and would, thus, grow with time as the universe grows. Its origin and nature remain unknown, but its effect can be measured and duly represented in Einstein's equations of general relativity.

dark matter: A hypothetical form of matter that accounts for 90 percent of all the gravity in the universe. We have never seen dark matter but infer its presence from its gravitational effects on ordinary matter.

density: A measure of how tightly packed is the material that comprises a substance. Density is formally the mass of an object divided by its volume.

Doppler shift: Named for the 19th-century German physicist Christian Doppler, who first measured the change in the pitch (frequency) of a sound as the sound-emitting object approaches or recedes from the listener. This shift in frequency was determined to be a general phenomenon for any form of wave.

Drake equation: A means to divide the overall probability of finding life in the galaxy into a set of simpler probabilities that correspond to our data and our preconceived notions of the cosmic conditions suitable for life as we know it. In the end, you are left with an estimate for the total number of

technologically proficient civilizations in the galaxy with which you might communicate with radio waves or by some other technology-based methods.

dust cloud: Gas clouds in interstellar space that are cool enough for the slow-moving atoms to combine and form large, complex molecules.

ecosystems: A community of organisms and the environment in which they live make up an ecosystem.

electron: The common subatomic particle that is negatively charged. Found in equal numbers with the positively charged protons throughout the universe.

elements: The basic constituents of all matter. All matter in the universe is composed of 92 elements that range from the smallest atom, hydrogen (with 1 proton in its nucleus), to the largest naturally occurring element, uranium (with 92 protons in its nucleus). Although trace amounts of larger elements have been found in mines, elements larger than uranium are produced in laboratories.

endothermic: In nuclear physics or in chemistry, if less energy is released in a reaction than was available at the start, the reaction is called endothermic. (See **exothermic**.)

escape velocity: A special speed on all planets, stars, or anything with gravity at which a tossed object will never return. This speed is defined as the escape velocity. For all speeds less than escape velocity, the tossed object will return.

event horizon: The poetic name given to the bounding region around a black hole within which light cannot escape. It may be defined as the “edge” of a black hole. This term is also applied to the visible edge of the universe.

exobiology: The study of life elsewhere in the universe.

exothermic: In nuclear physics or in chemistry, if more energy is released in a reaction than was available at the start, the reaction is called exothermic. (See **endothermic**.)

fission: The splitting of larger atoms into two or more smaller atoms. If this occurs with atoms larger than iron, then energy is released. This is the source of energy in all present-day nuclear power plants. Also called *atomic fission*.

fusion: The combining of smaller atoms to form larger atoms. If this occurs with atoms smaller than iron, then energy is released. The primary energy source for the world's nuclear war arsenals and for all stars in the universe is fusion. Also called *thermonuclear fusion*.

galaxy: A system of typically billions of stars, gas, and dust that share a common center of gravity. Galaxies are the primary organization of visible matter in the universe.

gas cloud: Clouds of hydrogen, helium, and trace amounts of heavier elements; the primary components of interstellar space in the disk of spiral galaxies.

general relativity: Introduced in 1915 by Albert Einstein, it forms the natural extension of *special relativity* into the domain of accelerating objects. It is a modern theory of gravity that successfully explains many experimental results that were not otherwise explainable in terms of Newton's theory of gravity from the 17th century. Its basic premise is the *equivalence principle*, whereby a person in a spaceship, for example, cannot distinguish whether the spaceship is accelerating through space or whether the spaceship is stationary in a gravitational field that would produce the same acceleration. From this simple, yet profound, principle emerges a completely reworked understanding of the nature of gravity. According to Einstein, gravity is not a force in the traditional meaning of the word. Gravity is the curvature of space in the vicinity of a mass. The motion of a nearby object is completely determined by its velocity and the amount of curvature that is present. As counterintuitive as this sounds, it explains all known behavior of gravitational systems ever studied, and it predicts a myriad of even more counterintuitive phenomena that are continually verified by controlled

experiment. For example, Einstein predicted that a strong gravity field should warp space and noticeably bend light in its vicinity. It was later shown that starlight passing near the edge of the Sun (as seen during a total solar eclipse) is displaced from its expected position by an amount in exact accord with Einstein's predictions. Perhaps the grandest application of the general theory of relativity involves the description of our expanding universe, in which all of space is curved from the collected gravity of hundreds of billions of galaxies. An important and currently unverified prediction is the existence of *gravitons*, or *gravity waves*. These are the particles of gravity that communicate abrupt changes in a gravitational field, such as is expected in a supernova explosion.

heliocentric: Sun-centered. (Compare *geocentric*: Earth-centered.)

impact energy: The energy released when an asteroid or comet strikes the surface of a planet or any other cosmic object. In the collision, the impactor's kinetic energy is passed entirely to the object.

impact rate: The rate at which a planet has experienced impacts from celestial objects of a predetermined size.

impact record: The accounting of all confirmed impacts on a planet's surface.

isotope: A chemical element with fewer or more neutrons in its nucleus than is common in nature. All isotopes have the same chemical properties but different nuclear properties.

Kelvin temperature scale: Named for Lord Kelvin of the mid-19th century. He invented the scale where the coldest possible temperature is, by definition, 0 degrees. Its increments are the same as the Celsius scale. On the Kelvin scale, water freezes at 273.16 degrees and boils at 373.16 degrees.

killer asteroids: Asteroids large enough to cause the mass extinction of many or most of the species of a planet. A killer asteroid on Earth would, at a minimum, destroy all civilization.

kinetic energy: The energy of an object from being in motion. Mass also contributes to kinetic energy. For example, if a more massive object (such as a truck) moves with the same speed as a less massive object (such as a tricycle), then the more massive object will have more kinetic energy.

latent heat: The heat that is either absorbed or released by a substance whose physical state has changed, for example, when water changes from a liquid to a solid.

law: When a theory about a reoccurring natural phenomenon has been tested many times and not disproved, that theory becomes a law, like Newton's laws or Kepler's laws.

light year: The distance light travels in one year. At the speed of light, this distance equals 5,800,000,000 miles.

long-period comets: Comets on elongated orbits around the Sun, with periods of 200 years or more.

luminosity: A measure of the rate of energy output for an object, such as a star.

magnetic field: Moving charged particles are the sole producers of magnetic fields. These fields are regions of space that supply a force to other charged particles in the area. All magnets have two poles, which are often called *north* and *south*. If you represent a magnetic field with imaginary lines, then all lines form complete loops that extend through both magnetic poles.

mass: A measure of an object's material content. For example, a locomotive that is weightless in space has no less mass than a locomotive that weighs 100 tons on Earth. Note also that mass makes no reference to size. A beach ball is large, but it is certainly not massive. An anvil is massive, but it is certainly not large.

microlensing: Einstein's general theory of relativity describes the curvature of space-time in the vicinity of a mass. For high-mass objects, light from a distant object can be split into several paths, giving multiple images of

the same object. This effect, known as gravitational lensing, also works with smaller, planet-sized masses, but in these cases, which are called microlenses, the multiple background images do not split completely. Instead, the images fall on top of one another, brightening the light of the distant object.

molecular cloud: Gas clouds that are cool enough for molecules to form. Because these clouds tend to be very dense, they are the most likely places for the onset of star formation.

molecule: A chemical combination of elements that normally has very different properties from its constituent parts. For example, sodium and chlorine will kill you in a high enough dose. Together, as the molecule sodium chloride, they become ordinary table salt.

molten: In geology, this term is often used to describe melted rock. More generally, however, it is used to describe any thick liquid that is normally a solid.

momentum: angular, linear: The tendency of an object to remain rotating (angular) or to remain in motion in a straight line (linear). Momentum is one of the “conserved” quantities in nature; in a closed system, momentum remains unchanged.

neutron: A particle in the nucleus of all atoms (except for normal hydrogen). It is slightly more massive than the proton and contains no electric charge.

neutron star: The tiny remains (less than 20 miles in diameter) of the core of a supernova explosion. It is composed entirely of neutrons and is so dense that it is equivalent to cramming 2000 ocean liners into a cubic inch of space.

northern lights: See **aurora**.

nucleus: The central region of an atom that contains protons and neutrons.

oblate spheroid: A sphere that is squashed into a shape not unlike a hamburger. (Compare *prolate*.)

panspermia: The idea that life on Earth may have been delivered or seeded by asteroids or comets carrying microbes on or in them when they collided with the young Earth.

parallax: The change in position of a star or any other object that appears to occur just because your point of view has shifted. For example, your thumb held at arm's length will appear to be aligned with a different part of the background when you look with your left eye, then with your right eye.

period: Usually, the time for an object in orbit to complete one orbit. The period of the Earth is one year.

periodic table of elements: A sequence of every known element in the universe arranged by increasing number of protons in their nuclei.

photon: Massless particle of light energy. Its energy determines the part of the spectrum where it would be detected. High-energy photons are gamma rays; medium-energy photons are visible light; low-energy photons are radio waves.

plane: A conceptual region of space that is broad and flat. It is commonly used as a reference to orbits and orientations. For example, "The Earth's axis is tilted $23\frac{1}{2}$ degrees from the plane of the solar system."

planetary nebula: One of the few misnomers in astronomy, a planetary nebula is the gaseous remains of a dying red giant star. This photogenic phase of a star's life is short-lived, but nearly every star passes through this evolutionary stage, making them a common sight in the galaxy.

plasma: An extremely hot gas (like a normal star) in which most of the gas atoms' outer electrons have been stripped away, leaving a charge-filled cloud that responds to magnetic fields. It is sometimes called the *fourth state* of matter.

potential energy: The energy content that an object has by virtue of its chemical configuration or its position in space. For example, trinitrotoluene

(TNT) has enormous chemical potential energy, and water in a dam or at the top of a waterfall has enormous gravitational potential energy.

primordial: Generally refers to the chemical or physical conditions that existed at the formation of the Earth, Sun, galaxy, universe, and so on.

prolate spheroid: A sphere that is squished into a shape not unlike a hot dog or an American football. (Compare *oblate*.)

proton: The positively charged particles found in the nucleus of every atom. The number of protons in a nucleus defines the atom. For example, the element that has 1 proton is hydrogen. The element that has 2 protons is helium. The element that has 92 protons is uranium.

quantum foam: The field of quantum mechanics describes the behavior of matter on its smallest scales. General relativity describes the curvature of space and time in the vicinity of matter. During the early universe, the entire cosmos was the size of an atom, forcing a marriage between quantum mechanics and general relativity that yielded a churned, tangled structure to space-time known as *quantum foam*.

quasar: The small, but extremely luminous core of a galaxy where a super-massive black hole dines upon stars and gas clouds that drift too close. The swirling matter forms a disk that funnels down to the hole, radiating copiously along the way.

radiation: Any form of light—visible, infrared, radio, and so on. In this nuclear age, however, it has come to mean any particle or form of light that is bad for your health.

rarefied: Thin and wispy. Used almost exclusively to describe vacuous gases.

red shift: Lengthening of the measured wavelength of light due to the motion of the light-emitting object away from you. Because motion is relative, this shift also occurs if you are in motion away from the object.

redshift (one word): The general term used to describe the red-shifted spectra of nearly all galaxies in the universe. This universal redshift is primary evidence for our expanding universe.

relativity: General term used to describe Einstein's special and general theories of relativity.

revolution: Motion around another object. For example, the Earth revolves around the Sun. Often confused with *rotation*.

rotation: The spinning of an object on its own axis. For example, the Earth rotates once every 23 hours and 56 minutes.

singularity: When a very high-mass star collapses, no known force will stop it. Its material becomes smaller and denser and eventually becomes a black hole. Within the black hole, however, the material continues to collapse without limit, leading to a single point of zero size and infinite density, the singularity. Assuming that such a thing is impossible, this is evidence for the incompleteness of Einstein's general theory of relativity.

solar maxima/minima: The Sun undergoes an 11-year cycle of activity, as measured by the count of sunspots that move across its surface. When sunspots are peaking, the Sun is at solar maximum. When sunspots go away, the Sun is at solar minimum.

Space Interferometry Mission (SIM): A proposed space mission designed to make extremely accurate measurements of the positions and distances of stars in the galaxy, leading to the first direct measurements of extrasolar planets around other stars.

space-time: The mathematical combination of space and time that treats time as a coordinate with all the rights and privileges accorded space. The special theory of relativity demonstrates that nature is most accurately described using a space-time formalism. It simply requires that all events are specified with space *and* time coordinates.

special theory of relativity: First proposed in 1905 by Albert Einstein, it offers a renewed understanding of space, time, and motion. The theory is based on two *principles of relativity*: (1) The speed of light is constant for everyone no matter how you choose to measure it, and (2) the laws of physics are the same in every frame of reference that is either stationary or moving with constant velocity. The theory was later extended to include accelerating frames of reference in the general theory of relativity. The two principles of relativity assumed by Einstein have been shown to be valid in every experiment ever performed. Einstein extended the relativity principles to their logical conclusions and predicted an array of unusual concepts that include the following:

- There is no such thing as absolute simultaneous events. What is simultaneous for one observer may have been separated in time for another observer.
- The faster you travel, the slower your time progresses relative to someone observing you.
- The faster you travel, the more massive you become, so that the engines of your spaceship are less and less effective in increasing your speed.
- The faster you travel, the shorter your spaceship becomes—everything gets shorter in the direction of motion.
- At the speed of light, time stops, you have zero length, and your mass is infinite. Upon realizing the absurdity of this limiting case, Einstein concluded that you cannot reach the speed of light.

Experiments invented to test Einstein's theories have verified all of the above predictions precisely. An excellent example is provided by particles that have decay *half-lives*. After a predictable time, half are expected to decay into another particle. When these particles are sent to speeds near the speed of light (in particle accelerators), the half-life increases in the exact amount predicted by Einstein. They also get harder to accelerate, which implies that their effective mass has increased.

spectral type: Any one of several lettered designations that indicate the temperature of a star. In order from hottest to coolest the designations are: O, B, A, F, G, K, M. Historically, stars were classified solely according to features in their spectra. Letters were assigned, in order through the alphabet, to classes of stars. Later, this method proved to be less useful than a classification scheme based on temperature. Many stellar classes were dropped, and some were joined with others. What remains is a hodgepodge letter sequence that is the darling of mnemonic writers.

spectrum: Light after it has separated into its component wavelengths. The human eye detects wavelengths by colors.

sphere: The only 3D shape in which every point on its surface is the same distance from its center.

strong force of nature: One of four principal forces of nature. One which binds together neutrons and protons to make atomic nuclei.

sunspots: Small circular regions of the Sun's surface that are somewhat cooler than the surrounding areas. This temperature contrast makes sunspots appear dark against their brighter background. They move with the Sun's surface and tend to avoid the polar and equatorial regions. Sunspots commonly travel in pairs because of their association with magnetic fields. They come and go in "cycles" that define the 11-year period of solar activity. The average sunspot is about two or three times larger than the Earth.

supernovae: The explosion of a high-mass star that has just run out of fuel. After having fused hydrogen to helium, helium to carbon, and so forth until iron, which is endothermic in all reactions, the star collapses under its own weight, then explodes with a luminosity that rivals the brightness of the entire galaxy of stars that surround it.

surface tension: The tension at the surface of a liquid caused by the attraction of the molecules within the liquid toward one another. Surface tension is apparent in an overfilled glass of water, where the liquid surface actually rises past the rim of the glass.

telescope (gamma, X-ray, ultraviolet, optical [visible], infrared, microwave, radio): Astronomers have designed special telescopes and detectors for each part of the spectrum. Most parts of this spectrum do not reach Earth's surface. To see the gamma rays, X-rays, ultraviolet light, and infrared light emitted by many cosmic objects, these telescopes must be lifted into orbit above the absorbing layers of the Earth's atmosphere. Although all the telescopes are of different design, they do share three basic principles: (1) They collect photons, (2) they focus photons, and (3) they record the photons with some sort of detector.

Terrestrial Planet Finder (TPF): A proposed NASA mission designed to locate and image Earth-like planets around other stars. The brighter planets will be targeted for follow-up spectra where the signature of surface life may be found in the atmospheres of the planets themselves.

theory: A general principle that is widely accepted and is in accordance with observable facts and experimental data.

thermal energy: The energy contained in an object (solid, liquid, or gaseous) by virtue of its atomic or molecular vibrations. The average kinetic energy of these vibrating atoms and molecules defines temperatures.

thermodynamics: The study of heat as it interacts with other forms of energy and matter.

thermonuclear: Any process that relates to the behavior of the atomic nucleus in the presence of high temperatures.

tidal forces: The difference in gravity from one side of an object to another, creating a sustained stress that elongates the object in the direction of the source of gravity. In extreme cases, the tidal force will exceed the binding forces of the object, forcing it to break apart.

tunneling: An effect in quantum mechanics that has no analog in classical physics. Even though a particle might not have enough energy to cross an energy barrier, tunneling is the assured probability that the particle will get there in any case, similar to the example of a car driving through a mountain

instead of over it. The protons engaged in thermonuclear fusion in the Sun's core require tunneling to undergo fusion.

wavelength: The length of a repeating component of a wave. A very useful term that applies to sound, light, trucks in a convoy, ripples on the surface of water, and so on.

white dwarf: The end-state in the life of an intermediate-mass star where its nuclear fuel supplies have run out. In the process, the outer layers of the star expand to make a red giant, while the inner layers collapse to form a hot, dense, Earth-sized ball of matter—the white dwarf—laid bare as the outer layers float away into space.

Biographical Notes

Copernicus, Nicolaus (1473–1543), Polish astronomer: The greatest astronomer since Hipparchus, he is generally credited with restoring the idea of a Sun-centered, heliocentric universe. For nearly 1500 years, the Earth-centered, geocentric universe had been predominant.

Doppler, Christian (1805–1853), Austrian physicist: A distinguished physicist in his day, Doppler is best known for the spectral effect that bears his name. When an object in motion emits a wave of anything (such as sound or light), the natural frequency of the wave is increased if the object is approaching you and decreased if the object is receding. This general principle, the *Doppler shift*, reveals itself in train whistles, racecars, and the expanding universe.

Eddington, Sir Arthur (1882–1944), English astrophysicist: Eddington married his tandem knowledge of physics and astronomy to become the first astrophysicist. A brilliant scientist with a tireless interest in the latest and most important problems of the day, Sir Arthur was well known for conducting the first confirming measurements of the curvature of space-time, as predicted by Albert Einstein in his modern theory of gravity, which is better known as the general theory of relativity. Sir Arthur also attempted to deduce the nature of stars and other cosmic phenomena from physical principles. Although not always correct, his efforts reliably stimulated further research by others.

Einstein, Albert (1879–1955), German-American physicist: Einstein's contributions to our physical understanding of the universe rival only those of Isaac Newton. In 1905, he proposed his revolutionary special theory of relativity, where space and time are conjoined. This conceptual framework allowed him to make counterintuitive predictions about the mass, the flow of time, and the physical dimensions observed of an object as its speed approaches the speed of light. Followed by his 1916 theory of gravity—the general theory of relativity—Einstein interpreted gravity as the curvature of space-time through which matter falls, rather than as a conventional force

that acts at a distance. To date, all reliable experiments that have ever been conducted have confirmed the predictions of relativity.

Galilei, Galileo (1564–1642), Italian physicist: Although not the inventor of the telescope, Galileo may have been the first to look up with it. What lay before him was a garden of cosmic knowledge that permanently altered the landscape of scientific thought. His discoveries ranged from simple observations that the Moon's surface is not smooth (as presupposed) to the fact that Earth cannot be the center of all motion because Jupiter has a set of moons all to itself. His heretical findings and his relentless ego got him in trouble with the Catholic Church. He was found guilty and, to avoid torture, was forced to sign a confession that renounced his data. Galileo (rather, his corpse) was found innocent of all charges somewhat later (350 years) by Pope John Paul II.

Gamow, George (1904–1968), Soviet-American physicist: Gamow was a distinguished physicist at a time when human understanding of the atom and the universe took fundamental leaps. In 1946, he proposed what came to be known as the *Big Bang* model of the universe, which came with testable predictions of the abundance of heavy elements and of a background remnant of microwaves from the original explosion.

Hertz, Heinrich Rudolf (1857–1894), German physicist: Hertz demonstrated that radio waves are just another form of electromagnetic waves, akin to visible light, thus enabling the intellectual unification of previously disjointed forms of energy. The familiar unit of electromagnetic frequency is named in his honor.

Hubble, Edwin Powell (1889–1953), American astronomer: Among many seminal contributions to observational astronomy, Hubble discovered the expanding universe in 1929. Law and boxing were two early interests of his before he turned to the heavens.

Humanson, Milton Lasell (1891–1972), American astronomer: Best known for his work on the 100-inch telescope at the Mt. Wilson Observatory and, later, the 200-inch telescope at Mt. Palomar, Humanson obtained spectra of galaxies in the late 1920s and for decades to follow. His data enabled Edwin

Hubble to further extend his discovery that distant galaxies recede faster than nearby ones.

Kant, Immanuel (1724–1804), German philosopher: Among astrophysicists, Kant is best remembered for having proposed in a 1755 essay the “nebular hypothesis” to explain the origin of the solar system. Kant suggested that a large spinning gas cloud would flatten as it collapsed under its own gravity. A large central nucleation would form the Sun, while smaller nucleations would form the planets. Although various modifications to this suggestion have been required over the years, the basic idea and scenario are correct. Extending this idea to the entire galaxy, Kant also supposed that the fuzzy “stars” in the sky were other galaxies—*island universes* distinct from our own, an idea later confirmed by Edwin Hubble in 1929.

Kepler, Johannes (1571–1630), German mathematician and astronomer: Kepler proposed the first truly predictive mathematical theory of the universe through his laws of planetary motion. Isaac Newton would later show that Kepler’s laws are derived easily from more basic theories of gravity.

Laplace, Pierre Simon (1749–1827), French mathematician and astronomer: Duly famous in the annals of astronomy for many reasons, Laplace, most notably, updated Isaac Newton’s laws of gravity to allow for the hard-to-predict multiple effects of many sources of gravity acting simultaneously. In what is today called *perturbation theory*, Laplace’s technique allowed one to calculate planetary orbits with unprecedented precision. In the face of this enlightened understanding of celestial motions, Napoleon Bonaparte once commented to Laplace that there was no mention of God in his book, whereupon Laplace replied, “Sir, I have no need of that hypothesis.” Laplace also postulated the existence of an object with such high gravity that light might not escape, and he proposed independently that the system of planets owes its origin to a collapsing, flattening, rotating gas cloud.

Lippershey, Hans (c. 1570–1619), Dutch optician: Credited with being the first person to assemble two lenses in such a way that objects appear closer to the person who looks through them. This invention is known as the telescope.

Lord Kelvin: See **Sir William Thomson**.

Michelson, Albert (1852–1931), American physicist: Best known for his development of the *interferometer*, which is an extremely sensitive optical device that can be used to measure, among other things, the speed of light, to unprecedented precision. Teamed with Edward Morley in 1887, he demonstrated that the speed of light was independent of the direction that Earth moved through the ether, thus casting serious doubt on its existence as a medium through which light must travel. In 1907, Michelson was the first American to ever receive the Nobel Prize.

Morley, Edward Williams (1838–1923), American chemist: See **Albert Michelson**.

Newton, Isaac (1642–1727), English physicist: A famous quote from Newton proclaims that if he can see farther than other men it is because he stands upon the shoulders of giants who came before him. This may have indeed been true (especially if the giants are Copernicus, Kepler, and Galileo), but the real secret to his distant vision might simply have been that he was surrounded by intellectual midgets. In spite of this, Newton spent his most scientifically productive years alone, during which he discovered the laws of gravity and many laws of optics and invented calculus. Surely one of the greatest intellects ever to walk the Earth, a statue of him in Cambridge, England, proclaims: “Of the human species, the brilliance of Isaac Newton reigns supreme.”

Slipher, Vesto Melvin (1875–1969), American astronomer: An accomplished astronomer who is best known for obtaining spectra of spiral nebulae that enabled Hubble to conclude that the spiral nebulae were indeed entire galaxies external to our own Milky Way and that nearly all were moving away from us.

Thomson, William (Baron Kelvin of Largs) (1824–1907), British physicist: A precocious lad, William Thomson graduated from the University of Glasgow at age 10. He became a major contributor to human understanding of the electromagnetic force and the study of thermal energy, better known as *thermodynamics*. The Kelvin absolute temperature scale, where zero degrees is the coldest possible temperature, is named in his honor.

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